Tracking Fixations and Saccades during Reading to Determine the Optimal Text Perceptual Features for Student Reading Comprehension

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Abstract

Developing reading comprehension skills is essential to the success of young adults in school and in the workforce. Past studies have shown increased text disfluency - how hard it is to read a passage - increased engagement with a text resulting in improved reading comprehension. Furthermore, text disfluency is a function of text perceptual features, such as font size or style. Other reading studies show that particular eye motions indicate higher comprehension. This study sets a goal to determine which typographical passage parameters are optimal for the reading comprehension of students by using an eye tracking mechanism during reading which is attached to the consumer via a wearable pair of glasses. With the results of this study we will determine which perceptual text features lead to the best comprehension using the "optimal eye movement" pattern of saccades and fixations during reading.

1.0 Introduction

Poor reading abilities are correlated to an increased risk for school dropout and negative self confidence and mental health effects (McArthur & Castles, 2017). Reading comprehension can be aided by optimizing text perceptual features (e.g. font size or style) which encourages eye movements conducive to comprehension (Oppenheimer, et al., 2010). This project will assess the possible perceptual features and related levels of disfluency (how difficult it is to read a word) which lead to the "optimal eye movement" pattern during reading and are contributing to the heightening of reading comprehension of students.

1.1 Background

While reading, the eye moves in a non repetitive pattern of saccades, fixations and regressions. These patterns, which have been shown to indicate reading comprehension level, are affected by perceptual features, such as, font size and type (Oppenheimer, et al., 2010).

1.1.1 Eye Motions

Fixations are short pauses of eye movement. During a fixation, the eye focuses on a single location, which is necessary to retain visual information. Fixations last as long as it takes for the eye to register and retain visual stimuli (typically between 200-300 ms) (Tobii, 2023) (Martinez-Conde, et al., 2004). Saccades, which can be either voluntary or involuntary, occur when each eye simultaneously changes rapidly from one target to another — moving the eye between fixations. Saccades differ in direction and duration, lasting from 100-1000 ms (Tobii, 2023). A subclass of saccade is the regression, eye movement back to a previous fixated spot.

1.1.2 General Eye Movement during Reading

While reading, the frequency of fixations per word may vary and a single word may be fixated on more than once. Ideal regressive frequency for an above average high school student (average adult reader) accounts for 10% to 15% of total saccadic movement according to Pitt Education researchers. A person who tends to make fewer eye fixations and/or regressions per word during reading often has an elevated reading pace compared to a person who fixates at a higher rate.

When reading, the eye does not necessarily fixate on every word, and fixation durations on different words can vary. Fixation duration is determined based on processing loads (the amount of mental strength or concentration it takes to register, analyze, and comprehend visual stimuli or patterns). Above average processing loads occur at infrequent words, sections of text where information is integrated, and during moments of inference, all resulting in longer fixation time. It is believed that the duration of fixation of particular words is the amount of time it takes readers to understand the word (Marcel, et al., 1983).

Large regressions are done with the purpose of re-processing previous text and revising understanding of text to better comprehend. Small regressions are done with the purpose of reanalyzing words to correct inaccurate word recognition.

1.1.3 Factors influencing Eye movement during Reading

Researchers at Pitt Education investigated the effect of text variables on fixation duration and probability for individual words. While fixations generally last for 200-300 ms, they can range from 50-500 ms. Text difficulty causes the average of the fixation durations to increase, the mean saccade length to increase (slower/longer saccades), and the number of regressions to increase. It is established that high frequency words (commonly occurring) are fixated less than low frequency words. The high frequency words are also more likely to be skipped completely during reading. The predictability of words in a phrase was also identified as a variable since words that are likely to occur due to surrounding context are fixated on less than unpredictable words. Function words such as articles (the, and, etc.) are fixated on less than content words and are skipped more. The degree of intended comprehension (skimming/speed reading vs. detailed reading/reading for complete comprehension) also influences words skipped and fixations, with a higher degree of intended comprehension increasing fixations and decreasing word skipping. Ultimately fixation duration and frequency is mostly influenced by the reader's cognitive proficiency in relation to reading level. Disfluency describes how hard it is for people to read the text. It has been shown that disfluency supports reading comprehension ability (Oppenheimer, et al., 2010).

1.1.4 Reading Comprehension and Perceptual Text Features

According to the "RAND Model of Reading Comprehension," comprehension relies on the ability to examine the contribution of reader characteristics, text perceptual features, and outside factors (Katzir et al., 2013). Typographical elements of text affect the appearance (e.g. font, text size, spacing, background color, etc). It is a common misbelief of many education researchers that reducing the cognitive load is helpful for students who are trying to learn and comprehend. Reading disfluency encourages frequent pauses at unknown or hard-to-read words and directly leads to an increased processing load. Therefore, reading disfluency has a direct relationship with the reading comprehension of the reader (findings are summarized in Table 1).

Table 1: Researchers Findings Related to Relationship of Cognitive Load and Comprehension	
Bjork (n.d.)	More challenging passage leads to better long term reading comprehension (Craik, F. I. M., & Tulving, E., 1975).
Diemand-Yauman, et al, in 2011	purposely increased disfluency, produced by an increased cognitive load which is generated by altered passage parameters, promotes reading comprehension of students of high school age
Faber, et al., in 2017	Increasing the cognitive load by promoting disfluency reduces the reader's susceptibility to mind wandering, thus increasing comprehension abilities. It does so by raising surface-level processing and reducing attentional resources that can be used for mind wandering
Oppenheimer in 2010	harder to read fonts led to higher reading comprehension in a controlled environment. He found that perceptual disfluency is desirable for teachers attempting to promote reading comprehension.

1.2 Literature review

1.2.1 Eye Movement during Reading of Proficient Readers (Optimal Eye Movement during Reading)

Rayner et al. in 1998 used eye movement to determine the cognitive load occurring during multiple tasks. The data record allows operators to examine the processing demands at a global level of the text, a sentence level, and the local level. Changes in level difficulty can be shown through increased or decreased reading times, probability of fixations, and the likelihood of regressions to certain parts of the passage.

Table 4: Ideal Reading Comprehension Eye Movement Averages		
	Average Number per Word	Average Duration
Fixations	Grade 10: 0.99 Grade 12: 0.94 (Spichtig, 2017)	250 ms (Rayner, 1998) Range: 60-500 ms (Rayner, 1998)
Regressions	Grade 10: 0.12 Grade 12: 0.10 (Spichtig, 2017)	

1.2.2 Visual Tracking

Currently, eye tracking devices are used in fields ranging from user experience testing for software applications to further researching eye movement in particular situations. Each eye tracking application has unique requirements. Table 5 shows a comparison of the most common eye tracking device types based on *Different Kinds of Eye Tracking Devices* (Mento, 2020).

Table 5: Types of Eye Tracking Devices

Types of Eye Tracking Devices	Summary	Pros	Cons
Head-Stabilized	•Constrains head movements •Bite-bar, Chin rest	•High accuracy and precision •Control visual experience	•Limits comfort and natural interaction
Remote	•Is not in contact with participant •Employs pupil center and corneal reflection method to track	•Promotes natural interaction •Compatible with EEG	•Limits working area available for participant •Can be hindered by excessive head movement •Only one participant can be visible to camera •Is not compatible with sunlight
Mobile	•Head mounted •Wearable device •Camera in visual path of eye •Second camera recording field of vision	•Easy to wear in “real-world” experiments •Compatible with EEG	•Is not compatible with sunlight •Extreme eye movements are hard for it to track •Does not have set coordinate system
Integrated/ Embedded	•Tracking devices embedded in virtual reality devices •Tracking devices embedded in augmented reality devices		

After considering all the possibilities, head stabilized eye tracking was determined to be the most reliable method for this study because it limits possible excessive head movements which could make positional eye tracking difficult.

1.3 Problem Statement

Difficulties in reading comprehension are a common problem experienced by many students, often resulting in lower grades and lowered self esteem. Various studies have measured saccades and fixations during reading in order to understand how eye motion is related to reading comprehension. Other studies have tested how text perceptual features have affected reading comprehension. This project will use eye motion analysis to determine how text features affect reading comprehension with the goal of providing personalized optimal text features to individual participants.

2.0 Methods Overview

Subjects were asked to read three passages (A, B and C) of one paragraph length, each with increasing disfluency. During reading, the subject's eye position was captured on video for post-processing. Two sets of tests were completed (test with only font as parameter and test with multiple parameters). The passages utilized arial, times new roman, and comic sans fonts. The results were determined by the regressive percentage of saccades, fixation frequency, and average fixation duration.

In the first set of tests, multiple parameters were used to amplify the disfluency level including font, underlining and bolding. The second set of testing only contained differences in font. The parameters are enumerated in the table below, in both tests passage C represented the most disfluent sample.

Table 6: Passages, Fonts, and Types

Passages	Font	Other (in multi parameter test)
A	Times New Roman	**Bold**
B	Arial	<u>Underlined</u>
C	Comic Sans	<u>Underlined</u>

2.1 Specifications

The eye-tracking prototype requires a clear video and near normal view of the eye in order to complete pupil detection during testing. The camera placement must provide a clear field of vision to allow the participant to read. The hardware needed to be adjustable in height so that it could comfortably fit participants of all heights. The camera used was a Pi Camera V2 attached to a Raspberry Pi Model 4.

2.1.1 Hardware

Figure 2: Experimental test with the inclusion of hardware depiction

The final hardware involves a (connected) head and chin rest adjustable in the y-direction in order to fit each participant's height. Connected to the headrest is the camera, which is mounted on a 3-axis adjustable leg.

Before each subject test, both the head and chin rest and the camera orientation were adjusted for subject comfort and image clarity.

2.1.2 Software

Videos are processed on a macbook using a modified version of the HoughCircles function, originally taken from OpenCV libraries. The HoughCircle program provides frame-by-frame x and y coordinates for the position of the circular iris with the center of the pupil serving as the circle center. The positions are then mapped on a grid for the observer, and put into a list from which the progression of eye motion can be analyzed. Occasionally the HoughCircle function will identify a circle in the field of view that is not centered on the iris. For example, it may identify a circle based on the shape of the eyelid, or an adjacent eye lash. To avoid the software indicating these outlier coordinates as saccades, an error adjustment system was put in place. Since typical eye motion was limited to a saccade of 11 pixels or less, and outlier data is typically 30 pixels or more, it is easy to remove the outliers. In these cases, a coordinate position

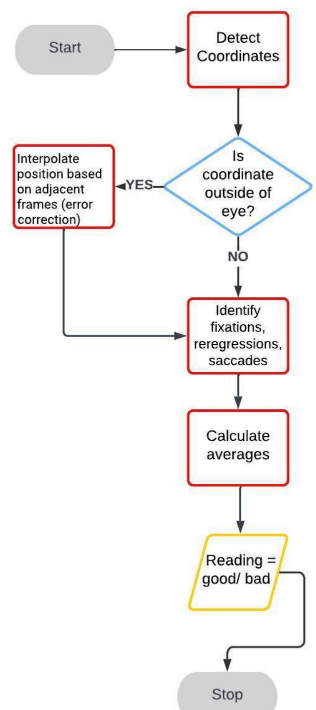

Figure 3: Progression of algorithm when finding and processing eye position.

is interpolated between adjacent frames to allow fixation and saccade statistics to be meaningful. When the pupil was properly detected there was still a remaining uncertainty of ±5 pixels. This value was determined experimentally through a test where the standard deviation was taken from a test containing a single, sustained fixation.

2.2 System Validation

To validate the accuracy of fixation and saccade identification, a subject was instructed to fixate once for the duration of a test. Raw video was watched frame by frame and fixations were manually counted and compared to the results quantified by the algorithm.

Initial comprehension protocol included a multiple choice test, however this part of the project remains incomplete and will be developed in the future.

3.0 Results

Position plotting was used to validate our results. Figure 4A shows the results of a subject reading a very large font to exaggerate eye movements. Figure 4B shows the same test with a small font.

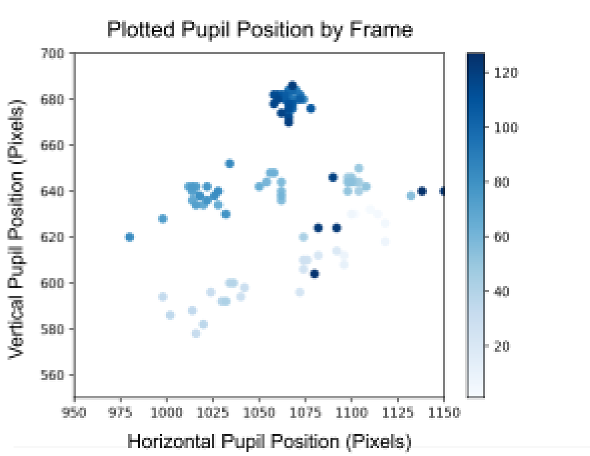

Figure 4A: Pupil Position by Frame While Reading 400 pt. Font from a 2 ft. Distance

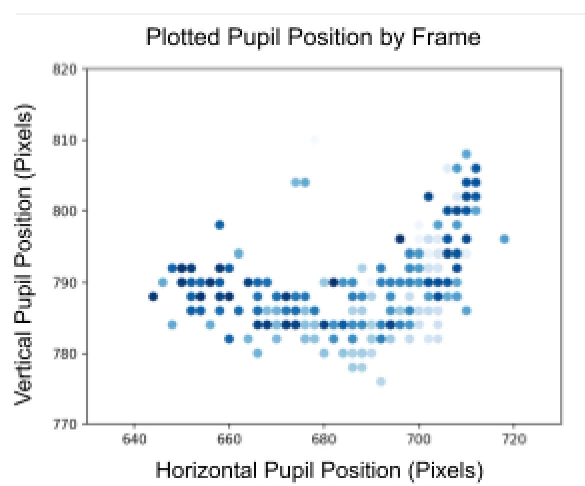

Figure 4B: Pupil Position by Frame While Reading 14 pt. Font from a 1 ft. Distance

It is clear that eye fixations on individual words are not resolvable while reading at the small font. The increasing in darkness of the points indicates the passage of time through the test with darker colors signifying points later in the test. Plot coordinate (0,0) reflects the top left corner of the page the subject reads resulting in the appearance of an inverted coordinate system. Because of this, participants were instructed to read from a closer distance so that eye movements are distinguishable.

Five subjects were each given three equivalent reading level passages to read, each with a different font (Figure 5) or in the multiparameter test (Figure 6). The height of each bar in Figures 5 and 6 indicates the number of fixations per frame. Higher rates indicate higher disfluency. The error bars were determined experimentally. A subject performed a fixation on a single point through the normal duration of a trial. The difference between the single fixations and the computed number of fixations yielded the error margin (0.019 fixations per frame).

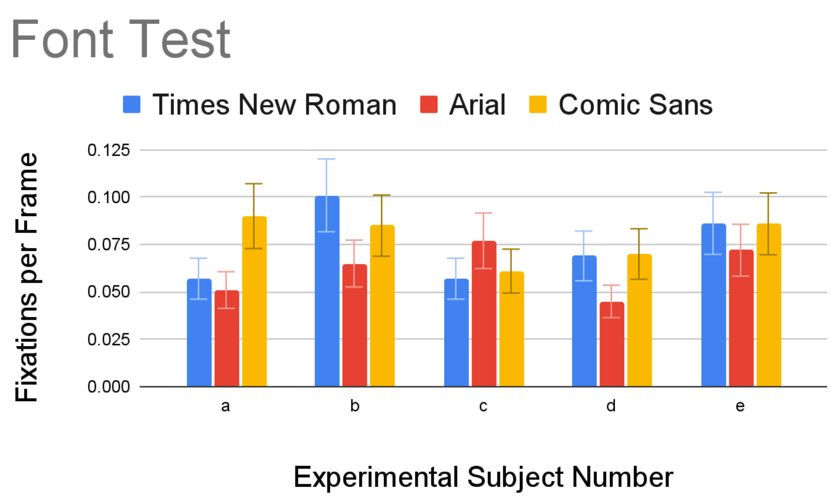

Figure 5: Calculated Fixation Rate Comparing Three Passages with Different Fonts

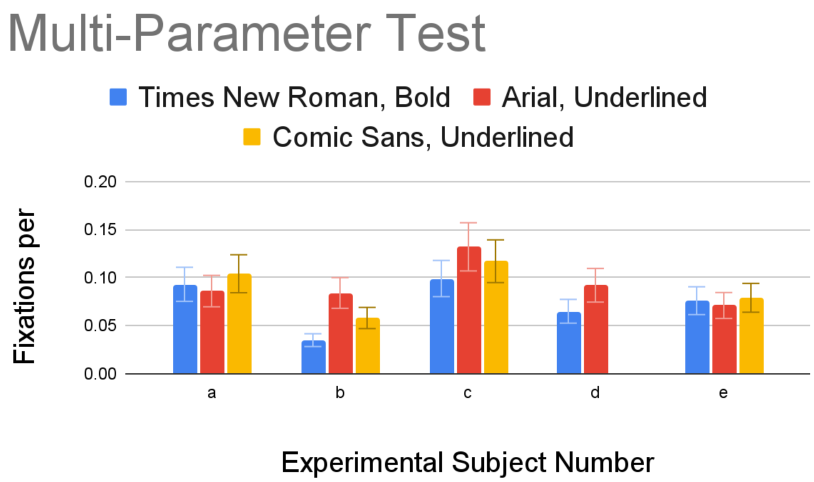

Figure 6: Calculated Fixation Rate Comparing Three Passages that Simultaneously Employ Different Perceptual Features

4.0 Discussion

An eye tracking device was successfully developed to quantify eye motion during reading, and determine which textual parameter in each test yielded the highest fixation rate. The higher the fixation rate, the more often the subjects fixated meaning that they took in more of the passage because material absorption occurs during fixations. For example, in Figure 5; *subject a* showed the highest fixation rate while reading comic sans, meaning it was the most disfluent (difficult to read) font for that participant causing them to spend more time reading it. Once comprehension validation can be implemented, connections can be made between fixation rate and comprehension. In the tests in which the fixation rate was very similar across different passages (Figure 5: d-e), the experimental subject did not have a significant reaction to that parameter test such that the two similar passages can be deemed equally/near equally suitable for them.

Most tests produced poor (high) regression frequency regardless of the disfluency of the reading parameters. On average, tests found that 50% of saccades were regressions which goes beyond the ideal 10-15%. Low detection precision of the HoughCircle function (±5 pixels) is the largest contributor to this error. Another factor is the inability for the program to differentiate between regressions and return saccades (regression to the next line of text). Fixation duration ranged between 4-9 frames and never went above the upper threshold of 15 frames per fixation. The most reliable determinant in this study was the fixation frequency which ideally ranged between 0.03 and 0.06 fixations per frame (equivalent to 0.8 - 1.2 fixations per word).

The error bars are primarily represented by the HoughCircles method of detection. These errors do not include the 50% of tests that were not included due to the algorithm not identifying the eye reliably or at all. Increasing the precision of the HoughCircles or implementing a more reliable eye detector is the biggest opportunity for increasing confidence in the results.

The adjustment element for the head and chin rest of the hardware was not as pertinent of an issue as originally expected. While testing, no participants requested adjustment, even after knowing it was an option. This could perhaps be attributed to the fact that the tests only lasted ten seconds each. In longer tests the adjustment element could prove to be useful for long term comfortability.

The multiparameter test (Figure 6) highlights the difficulty in isolating individual parameters and attributing discrepancies to certain parameters. The insignificant differences in those tests limit the ability to accurately ascertain any meaningful variations in disfluency levels. Future testing with only one parameter for each test will more clearly show connections between reading parameters, eye movement, and therefore reading comprehension.

Comparing reading comprehension predictions with output from our study will be an important next step in the project. Methodology for testing reading comprehension already exists and once the software determines whether or not the participant comprehended well, it could be validated using question and answer reading comprehension tests.

This device was developed to be used as a research tool in a controlled environment. Further development could also make this device portable, allowing subjects to be alerted should the text they are presented not yield high comprehension rates based on their eye patterns. In principle, the hardware and software are all portable (a python implementation on Raspberry Pi hardware). So moving to a mobile platform and allowing testing to occur in real-time situations could prove to be beneficial.

5.0 Conclusion

This study produced a prototype system to evaluate a participant's optimal text perceptual features. A head and chin rest prototype connected to a camera attached to an adjustable leg has been created to properly record eye movement during reading. The two part software processing made use of a modified HoughCircles algorithm to identify the iris position and calculate specific eye movements while reading. Overall the project is low cost and potentially portable, which could be helpful for students all across the world in improving their reading comprehension.

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