VISUALS IN THE MIND'S EYE:
INVESTIGATING GRAPH COMPREHENSION IN STUDENTS WITH DYSLEXIA

By

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To my grandmother

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Visual displays are commonly used to convey information. Graphic depictions of information are frequently recommended for individuals who have dyslexia because visual displays are thought to make information easier to understand. However, there is a dearth of research regarding the way individuals with dyslexia use visual representations or interpret information presented in the visuals. Little is known, especially, about the effect of graphic factors (e.g., type of graph, type of information to be interpreted from the graph) and subject factors (e.g., reading ability, working memory) on the individual's ability to comprehend information shown in graphs.

This project is designed to make progress toward ameliorating this problem. The *primary goal* of this project was to determine how individuals with dyslexia interpret graphic representations. The *secondary goal* was to investigate the extent to which cognitive abilities influence comprehension of graphically-presented materials. College students with dyslexia were compared with age-matched typical readers on graph comprehension tasks varying in graph types, graph complexity, and graph interpretation questions. Students with dyslexia were significantly less accurate and took more time than age-matched controls on graph

comprehension tasks, and this difference was more robust for the more complex graphs and questions. Also, there was a high correlation between working memory and graph comprehension for the students with dyslexia but not for the typical readers. These results underscore the necessity of conducting research on alternative and augmentative strategies for learning that are typically recommended for individuals who have reading disabilities and support the need for explicit instruction in graph interpretation for students with dyslexia.

CHAPTER 1
INTRODUCTION

In today's multi-media society, people are increasingly exposed to information that requires visual processing, such as graphs, tables, charts, and diagrams in both academic and non-academic settings. Visual displays are used, in large part, to make quantitative and qualitative information easy to understand (Tversky & Schiano, 1989). Thus, graphs have been widely used to facilitate readers' comprehension for numerous purposes such as comparing sets of data and examining trends in how data change over time (e.g., Guri-Rozenblit, 1989; Levis & Lentz, 1982; Palmar, 1978). Educators frequently encourage students with learning difficulties to use visual aids (e.g., a graphic organizer) to assist them with text comprehension (Murphy, 2005). There is, however, a dearth of research regarding whether the visual displays really facilitate learning. In fact, some researchers have reported that people do not obtain the expected advantages with visual representations (e.g., Mayer, 1993; Shah, Hegarty, & Mayer, 1999).

Developmental dyslexia is the most common language-based learning disability (Lyon, Shaywitz, & Shaywitz, 2003). The majority of research on dyslexia has focused on examining information processing presented in text formats (Shaywitz & Shaywitz, 2005; Vellutino, Fletcher, Snowling, & Scanlon, 2004 for reviews). However, recent research on the influence of specific cognitive processes on the performance of individuals with dyslexia on tasks presented in different modalities (e.g., auditory, visual), has encouraged researchers to explore a wider range of processing skills in this population. In fact, several studies have identified cognitive functioning impairment in persons with dyslexia in the areas of working memory and processing speed (e.g., Ackerman & Dykman, 1993; Berninger, et al., 2006; Cain, Oakhill, & Bryant, 2004; Cohen, Netley, & Clarke, 1984; Jorm, 1983; Kail, Hall, & Caskey, 1999; Katzir, et al., 2006). Also, studies have shown that individuals with dyslexia have problems with both maintenance/storage (e.g., Brunswick, McCrory, Price, Frith, & Frith, 1999; McDougall & Donohoe, 2002; Pennington, Cardoso-Martins, Green, & Lefly, 2001) and manipulation requiring processing (e.g., Bronsnan, et al., 2002; Smith-Spark, Fisk, Fawcett, & Nicolson, 2003; Swanson, 1999) of information. Findings from these numerous studies of individuals with dyslexia suggest that specific information processing abilities may be impaired across modalities (e.g., visual and/or auditory modalities). Hence, it is reasonable to hypothesize that similar processing difficulties would be evident in their interpretation of graphically displayed information.

Researchers have studied how we perceive meaning from graphs (e.g., Carpenter & Shah, 1998; Hegarty, Meyer, Narayanan, Freedman, & Shah, 2002; Pinker & Freedle, 1990) and collectively, suggest that processing a graph is a function of complex interactions among the pictorial properties of the graph, task, and graph reader's ability (Peebles & Cheng, 2003). First, the pictorial properties of graphs, including graph type and graphic complexity, have captured the attention of researchers. For example, there are different perspectives on the pictorial feature of graphs. Some researchers support the *perceptual feature view* which suggests that the representation of pictorial contents can be different depending on graph types such that each type of graph activates different representations (Lohse, 1993). Other researchers support the *invariant structure view* which suggests that graphs share common characteristics (Peebles & Cheng, 2003). In this approach, graphs that shares features activate similar representation.

Graphic complexity is another graphical property which plays a main role in graph processing. Carpenter and Shah (1998) used line graphs to examine the influence of graphic complexity on graph performance of college students. When the investigators added lines to depict data, they expected that their participants would need increased processing time to consider the third factor, *z*-variable, to interpret the relationship between x-axis and y-axis. College students were asked to interpret 12 pairs of line graphs. As hypothesized, students' graph interpretations were influenced by the number of lines (i.e., graphic complexity).

Secondly, researchers have used two types of questions to examine individuals' proficiency in understanding graphs (Curcio, 1982; Friel, Curcio, & Bright, 2001). The first type of question is referred to as a *point locating* question. With this question, participants are asked to read a question to determine what a single point on the graph represents (e.g. How much tin was produced in 1980?) The second type is called a *comparison* question. In this format, participants are required to compare two data points (e.g., Was more zinc or more cooper produced in 1982?).

Finally, the third factor affecting graph comprehension is the graph reader's ability to establish representations of data presented in the graph. Papafragou, Carruthers, Laurence, & Stich (2008) proposed the *Salient Hypothesis* in which the key linguistic features such as labels and keys in graphs become privileged and attract viewers attention (Salience hypothesis). As noted by Gentner & Goldin-Meadow (2003, p. 9), language offers "a lens on non-linguistic cognition" because it leads an individual's attention to features that are relevant to linguistic encoding.

Additionally, cognitive processes are central to graph comprehension. As our working memory temporarily stores only a limited amount of information (Baddeley & Hitch, 1974), multiple resources of graphs can potentially be a burden to readers (Hegarty & Steinhoff, 1997; Shah & Freedman, 2003) by taxing their memory resources and requiring them to split their attention (van Bruggen, Kirschner, & Jochems, 2002). Furthermore, information must not only be retained but also regulated and controlled during processing. The executive functions are responsible for attentional control including regulating, controlling, monitoring, and suppressing information (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001). Because there are multiple resources in a graph, readers should inhibit irrelevant information, activate relevant information, and update newly encoded information (Berninger, Raskind, Richards, Abbott, & Stock, 2008). Thus, it is important to investigate cognitive factors in an attempt to study important processes involved in graph comprehension.

To date, no scientific evidence has addressed the question, “Do persons with dyslexia have difficulty with comprehending graphs?” To answer this question, this study aims to: (1) compare the accuracy of graph comprehension in young adults with and without dyslexia using comprehension tasks; (2) compare overall reading time in young adults with and without dyslexia using eye tracking measurements; (3) compare eye gaze data for 6 specific graphic subregions (i.e., pattern, x-axis, y-axis, legend, question, answer) in young adults with and without dyslexia; and (4) test which factors among graphical properties and complexity, question types, and subject factors, including working memory and executive functions, affect their performance.

CHAPTER 2
LITERATURE REVIEW

This chapter reviews the pertinent studies that have informed the research on graph comprehension of young adults and presents the specific experimental questions addressed. Following a brief overview of various factors affecting graph processing, I discuss how dyslexia may affect graph comprehension. Next, I review methodology to measure graph performance of typical readers and present the significance for this study. Finally, the chapter concludes with an outline of the experimental research questions.

Definition of Graph Comprehension

The Organization for Economic Co-operation and Development (OECD; 1995) defined literacy as "the ability to use written information to function in society." Among three domains of literacy, document literacy refers to knowledge and skills required to comprehend information in various formats including tables and graphics (Murray, Kirsch, & Jenkins, 1997). Graphical literacy, also called *graphicacy*, is the ability to process and comprehend data presented in graph format. According to the OECD (1995), the graph is a core concept in literacy and needed for understanding social sciences, natural sciences, mathematics, etc (Kramarski, 2004).

Simkin and Hastie (1987; 1988) suggested four main perceptual processes by which people process graphs: anchoring, scanning, projecting, and superimposition. In anchoring, people select a portion of the graph as a baseline (e.g., 50% of a bar, midpoint). In scanning, people move their eyes from the anchor to the other side (e.g., from the midpoint to its edge). In projecting, people draw an image based on the data they obtained through anchoring and scanning. Finally, in superimposing, people mentally move elements (e.g., size, angle) of the graph to create overlap with another component of the image.

What Affects Graph Comprehension?

Researchers have studied how we perceive meaning from graphs (e.g., Carpenter & Shah, 1998; Hegarty, et al., 2002; Pinker & Freedle, 1990) and suggest that processing a graph is a function of a complex interaction among the pictorial properties of the graph, the given task, and the graph viewer's ability to process graph (Peebles & Cheng, 2003). A review of each of these factors affecting graph processing follows.

Pictorial Properties of a Graph

Fry (1983) defined a graph as "information transmitted by the position of points, lines or areas on a two-dimensional surface (p.5)". Upon initial consideration, graphs might seem be the simplest ways to convey information visually, yet they are actually quite complex in terms of their structure, employing several structural components (Kosslyn, 1989; Parmar & Signer, 2005). Friel et al. (2001) summarized four structural components of graphs. The first component is a *frame-work* (e.g., axes). The frame-work is used to represent the kinds of measurements and the data being measured. The second component encompasses the visual dimensions, called *specifiers*. These specifiers, such as lines on line graphs or bars on bar graphs, provide the data values of graphs. The third component is *labels*, such as titles and legends used to identify the type measurements being made. The last component is a *background* which includes the use of coloring or grid formats. A well-designed graph uses these features to clearly identify the information intended for interpretation and to facilitate the graph viewers' easy and rapid interpretation of information.

As mentioned in chapter 1, there are two prominent paradigms for discussing how features of graphs are processed. The *Perceptual Feature view* suggests that the representation of pictorial contents can be different depending on the graph types and that each type of graph activates different representations (e.g., Lohse, 1993; Ratwani & Trapton, 2008). For example, line graphs and bar graphs have different perceptual characteristics and they, consequently, activate a different schema. On the other hand, the *Invariant Structure view* suggests that graphs share some common characteristics (e.g, Peebles & Cheng, 2003) such as the x- and y-axes (i.e., Cartesian coordinate system) on line and bar graphs and that these similar frameworks share same underlying mental representations.

A Given Task

Graph viewers extract information from a graph to complete specific task(s) under various conditions. Questioning is a fundamental cognitive mechanism used to assess graph comprehension (Friel, et al., 2001). As noted previously, researchers have used two types of questions to examine individuals' proficiency in understanding graphs: '*point locating'* and '*comparison*' (Curcio, 1982; Friel, et al., 2001).

The point-locating question is characterized by extracting data from a graph and the comparison question focuses on interpolating and finding relationships of data from the graph (Friel, et al., 2001). The level of complexity of the two question types appears to differ. The information asked in the comparison questions is not explicitly represented in the graph, requiring more cognitive processing time/effort than the point locating questions (Duesbery, Werblow, & Yovanoff, 2011). Participants show more difficulty on comparison tasks compared to point locating tasks (e.g., Friel, et al., 2001; Monteiro & Ainley, 2004; Wainer, 1992), providing evidence that performance on graph comprehension can differ due to the question types used to elicit an interpretation from a graphic display.

Graph Viewer's Ability

The third factor affecting graph comprehension is the graph reader's ability to establish internal representations of data presented in a graph. Researchers have acknowledged that subject differences may have as much of an influence on comprehension processing as do the properties of the graph itself (Friel, et al., 2001). In spite of the importance of graph readers' abilities, few studies have investigated the abilities that individual's bring to the task of graph interpretation. However, researchers have suggested that subject factors associated with language and other cognitive abilities that may play an important role in visual comprehension (e.g., Berg & Phillips, 1994; Boden & Brodeur, 1999; Carpenter & Shah, 1998).

Language processing ability

The role of language ability in graph comprehension has not been widely appreciated. However, given that graph interpretation is typically accompanied by written text, both linguistic decoding and encoding abilities are relevant to visual processing (Gentner & Goldin-Meadow, 2003). Only very recently have researchers begun to focus on domains of language, such as relationships of vocabulary and visual comprehension. For example, Yang (2012) investaged graph skills of second language learners majoring in health sciences. They found that subjects' performance on graph interpretation was closely related to their lexical knowledge. As mentioned earlier, very little is know about the role of language in graph processing. Therefore, it is important to understand the role of language in graph comprehension.

Other cognitive processing abilities

Graph reading is a cognitive activity that requires information processing from several sources (e.g., axes, labels, values). Thus, it is important to understand the contribution of cognitive processing in visual interpretations (Huang, Hong, & Eades, 2006). Working memory serves the function of storing and manipulating verbal and visuospatial information (Baddeley & Hitch, 1974) and supports higher abilities such as comprehension and reasoning (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Shelton, Elliott, Matthews, Hill, & Gouvier, 2010). Several studies have attempted to explain the nature of working memory and the potential impact of working memory on cognitive processing (Duff & Logie, 2001). For example, the *resource* *sharing model* posits that working memory relies on one domain-general system (Cowan, et al., 2005). In this model, a single cognitive resource is used for both storage and processing (Just, Carpenter, & Keller, 1996). On the other hand, the *multiple resource model* posits that working memory taps several domain-specific and domain-general processes (Miyake, et al., 2001). In this multiple source framework, there is more than one subsystem acting concurrently to perform a specific task (Duff & Logie, 2001). Although these two models view the nature and function of working memory from different perspectives, both models distinguish between verbal and visual working memory systems. Considering the distinguishable characteristics of visual and verbal working memory and the close relationship between working memory resources and comprehension, it is necessary to investigate the features of working memory in both visual and verbal modalities (Tanabe & Osaka, 2009). Working memory capacity is commonly measured in an item span format task in which subjects' ability to recall increasingly longer sequences of words, digits, and objects (Waters & Caplan, 1996).

In addition to working memory capacity, executive function skills, such as regulating, controlling, monitoring, and suppressing information (Miyake, et al., 2001) may influence an individual's graph processing. Because of the multiple information resources (e.g., axes, legends, graphic patterns) in a graph, it is important to measure executive functions that subserve activating relevant information, inhibiting irrelevant information, and shifting between information (Martin & Allen, 2008). Executive functions are closely related to various cognitive abilities. Sesma, Mahone, Levine, Eason, and Cutting (2009) examined the contribution of executive functions in the reading comprehension of sixty children, aged 9-15 years. After controlling for attention, decoding skills, fluency, and vocabulary, executive functions were still an important factor in understanding written text. Busch, et al. (2005) investigated the relationship between executive functions and visual memory in patients with a history of traumatic brain injury. In a one year follow-up test, executive functions still played a key role in visual memory. Agostino, Johnson, and Pascual-Leone (2010) examined if executive functions were associated with word problem solving skills in 155 children in Grades 3–6. The investigators found that children's mathematical reasoning abilities were closely related to executive functions, especially in the case of multi-step problems. Research on executive functions has lead to better understanding of the development of various cognitive abilities (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000).

Because executive function is believed to consist of diverse functions, different sets of tasks have been administered to measure them (McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010). For example, Ashendorf and McCaffrey (2008) used the Wisconsin Card Sorting tasks (Grant, Jones, & Tallantis, 1949) to measure mental flexibility in 25 younger adults, aged 19-22 and 19 older adults, aged 63-89. Participants were asked to match stimulus cards by color, design, or quantity and verbally state their reason for each match. In another study conducted by Mahone, Koth, Cutting, Singer, and Denckla (2008), verbal fluency tasks were used to measure organizing and inhibitory functions in 46 children with either Tourette syndrome or Attention-Deficit/Hyperactivity. The children were required to name as many examples of animals and foods (semantic word fluency) within a given period of time. McCabe, et al.(2010) used mental control tasks to evaluate task maintenance abilities in 200 participants between 18 and 90 years of age. Mental control requires subjects to say well-known categories of information (e.g., the day of the week; months of the year) in forward and backward orders (Wechsler, 1997a).

Graph familiarity

Graph viewers' ability to connect different visual features to the meaning of those features is potentially influenced by their familiarity and experience with graphs (Shah & Hoeffner, 2002). Knowledge about graphs is referred to as having *graph schemata* (Pinker & Freedle, 1990) or *graph sense* (Friel, et al., 2001). Xi (2010) investigated whether graph familiarity of English language learners in US graduate schools influenced their performance on line graph tasks. It was found that participants who were more familiar with graphs obtained reliably higher content and organization scores in the line graph tasks than those with less familiarity with graphs. The study found that familiarity with graphs, in addition to familiarity with the contents depicted in the graphs influenced the students' graph processing. The manipulation of content knowledge in this graph study echoes the literature regarding the role of prior knowledge in learning (e.g., comparison of novice and expert). Langrall, Nisbet, Mooney, and Jansem (2011) selected middle school students from Australia, United States, and Thailand who had expert knowledge of a particular topic and those who had no great interest or knowledge in the topic and compared their performance on mathematical data analysis tasks. They found that students with context expertise were more likely to identify useful data for the task, and analyze and interpret the data compared to their peers. Cursio (1982) cautioned that the content in graphs and the vocabulary words used as specifiers may be factors that affect the individual's ability to comprehend relationships expressed in the graph. Therefore, it is important to ensure that graph viewers' prior knowledge about graphs and their contents do not hinder graph processing. Especially for people who have learning disabilities, knowledge on graphs and content can make a significant difference on their performance on graph tasks.

Dyslexia and Graph Comprehension

Definition of Dyslexia

The most current definition of dyslexia adopted by the International Dyslexia Association Board of Directors in 2002 states that “Dyslexia is a specific learning disability that is neurological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities (Lyon, et al., 2003).” Over the last two decades, the research literature on developmental dyslexia has focused on examining the word-level phonological processing deficits that are believed to lie at the core of this specific reading disability. More recently, specific cognitive deficits that are less directly associated with language, such as executive functions (Bronsnan, et al., 2002) and working memory (Beneventi, Tønnessen, Ersland, & Hugdahl, 2010) deficits have been observed in the behavioral profiles of many individuals diagnosed with dyslexia.

How Individuals with Dyslexia Process Graphs

Unfortunately, little is known about the graph comprehension abilities of individuals with dyslexia. To date, only one study by Parmar and Signer (2005) investigated line graph interpretation in children with learning disabilities. Seventeen fourth-grade and 25 fifth-grade students with learning disabilities and 23 fourth-grade and 26 fifth-grade students without learning disabilities were asked to complete four line graph tasks that include interpreting and constructing graphs. The students without learning disabilities significantly outperformed their peers with learning disabilities on all tasks. The authors emphasized the need to establish how individuals with language learning difficulties process graphically-presented information so that academic supports can be used, if necessary, to facilitate their comprehension in this area.

In spite of a lack of research in graph processing associated with dyslexia, it is likely that individuals with dyslexia will exhibit deficits in graph comprehension for two reasons; (1) A large number of studies have shown cognitive function impairments in persons with dyslexia in the areas of working memory (e.g., Ackerman & Dykman, 1993; Berninger, et al., 2006; Cain, et al., 2004; Cohen, et al., 1984; Jorm, 1983; Kail, et al., 1999; Katzir, et al., 2006); and (2) Studies have shown that some individuals with dyslexia exhibit executive function difficulties with tasks that involve the maintenance/storage (Brunswick, et al., 1999; McDougall & Donohoe, 2002; Pennington, et al., 2001) and manipulation of information (Bronsnan, et al., 2002; Smith-Spark, et al., 2003; Swanson, 1999). It is quite plausible, given the results of previous studies, that graphs may tax the memory capacity of individuals with dyslexia because they need to hold and integrate many elements (e.g., axes, labels, values, etc.) in memory in order to interpret graphs. Furthermore, individuals with dyslexia have difficulty connecting verbal labels to visual images (e.g., Boden & Brodeur, 1999; Gang & Siegel, 2002). This cross modal skill is used continuously when interpreting graphs (Ratwani, Trafton, & Boehm-Davis, 2008).

How to Measure Graph Comprehension

Reading Accuracy

Most researchers have investigated graph comprehension by analyzing participants' answers to specific questions. Question answering is considered a fundamental element of cognition and plays a major role in comprehension (Friel, et al., 2001; Graesser, Swamer, Baggett, Sell, & Britton, 1996). Carcio (1987) compared the graph comprehension of 204 fourth-grade and 185 seventh-grade students. The graph test consisted of three bar graphs, three line graphs, three circle graphs, and three pictographs. Six multiple-choice questions followed each graph. Two questions were literal items (e.g., point locating), two questions were comparison items (i.e., requiring comparison of two data points), and two questions were extension items (i.e., predicting a trend). The seventh-grade students reliably outperformed the fourth-grade students on the graph test; however, the differences in accuracy for the three question types were not addressed. Kramarski (2004) used multiple-choice questions to evaluate the effects of metacognitive instruction on the graph comprehension of 196 eighth-grade students. In the metacognitive instructions, students were guided to generate questions themselves and develop a strategy to answer the questions. Students who were exposed to metacognitive instructions performed more accurately on the multiple-choice questions. While multiple-choice questions have been used widely to assess study participants' comprehension because of their consistently high reliability, it has been recommended that other techniques be used in addition to the multiple choice format to increase the validity of assessing comprehension. (Levine, McGuire, & Nattress, 1970).

Eye Tracking

We ceaselessly move our eyes to take in visual information (Richardson, et al., 2007). Of most interest to researchers are *saccades*, the rapid eye movements around the visual field, and *fixations,* the places where our eyes stay fixed between the saccades (Rayner, 1998). Researchers have shown that if the available visual environment is relevant to the task at hand, the location of eye fixations indicates whether attention is being directed, a phenomenon called the *eye-mind hypothesis* (Just & Carpenter, 1980; van Gog & Scheiter, 2010). Additionally, researchers have reported that eye movements reflect underlying mechanisms that contribute to difficulty with performance (Rayner & Slattery, 2009). For example, fixation times are reliably longer and saccades are more frequent when reading irregular words (i.e., words which do not follow one-to-one correspondence between graphemes and phonemes) (Jones, Kelly, & Corley, 2007), listening to ambiguous sentences (Spivey, Tanenhous, & Ederhard, 2002), viewing incongruous objects (Henderson, Weeks, & Hollingworth, 1999), and detecting unfamiliar faces (e.g., Hirose & Hancock, 2007). Moreover, fixation times and frequency of saccades can distinguish between younger and older readers (Eurich, 1933a), unsuccessful and successful college students (Eurich, 1933b), physics experts and novices (Feil, 2010), beginning and experienced drivers (Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003), and second language learners and native speakers (Keating, 2009).

For examining individuals with dyslexia, eye-tracking is also a very effective tool (Rayner & Slattery, 2009). Some eye care specialists even assume that dyslexia is mainly due to oculomotor problems. They use simple eye-movement tests to diagnose dyslexia and oculomotor training to treat it (e.g., Pavlidis, 1981; Solan, Feldman, & Tujak, 1995). However, Rayner (1998) emphasized that attempts to replicate these studies have failed (e.g, Olson, Conneis, & Rack, 1991; Stanley, 1994). In his review paper, Rayner (1998) concluded that eye-movement difficulty is not a cause of dyslexia, but a symptom reflecting some underlying impaired mechanisms. Most commonly, researchers today regard dyslexia as *a language processing deficit* and study eye-movement as a reflection of a language processing disorder. Individuals with dyslexia have been found to show more frequent and longer fixations and saccades on tasks of phonological awareness, (Eden, Stein, Wood, & Wood, 1994), rapid automatized naming tasks (Jones, Obregón, Kelly, & Branigan, 2008), word reading (De Luca, Borrelli, Judica, Spinelli, & Zoccolotti, 2002), and text reading (Prado, Dubois, & Valdois, 2007) than their peers who do not have dyslexia.

The rational for using eye tracking in this study is that it provides a systematic method for examining how speed and accuracy influence the performance of individuals when interpreting graphs. Previous research has shown that individuals with dyslexia reliably take more time to respond to simple pure tone and lexical decision tasks than their nondyslexic peers although their responses are often accurate (Nicolson & Fawcett, 1994). Specifically, the tracking of eye movement allows for (a) determining the *amount of time* participants spend looking at specific areas (i.e., X-axis, Y-axis, and patterns) and (b) comparing the *eye movement data* (i.e., saccades, fixation) of typical and impaired readers while examining graphs and answering written questions in response to the data shown in the graphs.

Recently, eye-tracking has been frequently used to understand graphics (e.g., photos, graphs, animations) (Hyönä, 2010; Jarodzka, Scheiter, Gerjets, & van Gog, 2010). Holsanova, Holmberg, and Holmqvist (2009) investigated the influence of distance between text and graphics in eye movement behavior of thirty-one typical readers to test text-graphic integration. Participants were provided with a newspaper in two formats, a separated condition, in which text and graphic box were far from each other, and an integrated condition, in which the graphic was close to the text where the references needed to be explained. Participants more effectively integrated text and graphics when text and illustrations were physically closer.

In a study that focused on students' control of the pace of text and graphic information, Schmidt-Weigand, Kohnert, & Glowalla (2010) had 90 university students read/listen to multimedia instruction accompanying visualizations in a system-paced condition and another 31 students to read/listen to the instruction in a self-paced condition. Following an instruction, the students were tested on the content in the contexts of retention, transfer of information, and visual memory. Students in the self-paced condition spent more time on the important parts to complete tasks, compared to those in the system-paced condition. Carroll, Young, and Guertin(1992) analyzed eye movements of participants when they were asked to examine drawings with captions. They found that participants briefly scanned the picture first, then looked at the text, and then rescanned the picture more carefully.

These previous eye-tracking studies have shown that measuring eye movements provides us with greater understanding of how viewers approach learning information that requires them to integrate textual and graphic information. Mayer (2010) suggested that eye-tracking can contribute to the study of learning with graphics in both theoretical and practical ways. Specifically, eye-fixation measures provide an online observation of attentional control, linking visual perception and language. Also, eye-fixation measures provide information on instructional design for online learning. However, eye-tracking methods have their limitations, as they do not always give researchers accurate information on the success or failure of learning (Hyönä, 2010). The viewer may spend a long time looking at a given stimuli without adequate comprehension of its contents. For example, De Koning, Tabbers, Rikers, and Paas (2010) provided 40 psychology undergraduate students with an animation of the human cardiovascular system with and without visual cues to examine how visual attention was allocated when learning. The students' eye data included the number of fixations and the proportion of fixed time in specific locations. The findings revealed that students looked at cued as compared to non-cued content more frequently and for longer periods of time. However, the learning outcome measures, that included a comprehension test and verbal report, did not show cued content was learned more effectively. That is, students who looked at the cued animation did not necesarily comprehend the crucial relationships between different component of the cardiovascular system at a higher rate of accuracy. The investigators surmised that students with low knowledge might have difficulty understanding the content accurately and viewed the contents longer. They suggested that other factors that affect learning should be considered, too. Thus, the eye-tracking data should be supplemented with other performance measures (Cowles & Kim, 2011; Hyönä, 2010).

Rational and Significance of the Study

We are commonly exposed to visual representation of information. Children look at illustrations in storybooks when they are read to (Dockett, Whitton, & Perry, 2003), students are exposed to visual displays in textbooks (Cook, Wiebe, & Carter, 2008), and people read newspapers and magazines containing graphs and diagrams (Underwood, Jebbett, & Roberts, 2004). In addition, there is a widespread belief that visual aids facilitate learners' comprehension (e.g., Guri-Rozenblit, 1989; Levis & Lentz, 1982; Palmar, 1978), so educators frequently encourage them to use visual aids (e.g., graphic organizers) (Murphy, 2005). There is, however, a dearth of scientific evidence regarding whether the visual displays actually facilitate or impede learning.

There are numerous types of visual displays of data such as graphs, charts, maps, and diagrams (Kosslyn, 1989). Graphs have well-organized symbolic structure (Parmar & Signer, 2005) in which common properties and configurations of lines, colors, regions, etc. are all integrated to convey meaning (Habel & Acarturk, 2009). Thus, they can be a good starting point for investigating how visual entities affect comprehension.

Graphs serve to map perceptual features and conceptual messages; connections of these messages may be challenging for some people. In fact, investigators have acknowledged this possibility. For example, Freedman and Shah (2002) noted that while graphs are ubiquitous because they are perceived by educators, journalists, and other authors as more effective and less demanding in delivering information than text formats, comprehension of graphs can be very effortful and lead to incorrect decision-making. Also, Keller (2009) addressed the likelihood that graphing enables students to develop abstract thinking, yet some students are unable to correctly interpret graphs and have trouble developing the graphing skill. Further, Shah and Hoeffner (2002) concluded that school-aged children and even adults without learning difficulties commonly make an error in interpreting graphs and suggested the need to assess individuals' visual reasoning underlying external representational media like graphs (also see Gattis & Holyoak, 1996; Guthrie, Weber, & Kimmerly, 1993).

Considering that typical readers sometimes have difficulty interpreting graphs, searching for main ideas in graphs can be particularly challenging for people who have learning disabilities or a lack of experience with visual representations. This dimension of comprehension offers many opportunities for exploration. As mentioned before, only one study conducted by Parmar and Singer (2005) examined graph comprehension in students with learning disabilities and they found that they performed at a significantly lower level than their peers without learning disabilities, suggesting that the lack of the graphic comprehension skills in children with reading disabilities may be contributing to their failure to comprehend the textual information that is augmented by graphs. The authors stressed the lack of lack of research on graph comprehension of people with learning disabilities. This lack of data on the effects of graphs in the reading comprehension of individuals who have reading disabilities is somewhat surprising given that graphic displays are frequently used to assist students with learning difficulties to more easily access text contexts (e.g., Dexter, Park, & Hughes, 2011; Kim, Vaughn, Wanzek, & Wei, 2004; Nesbit & Adesope, 2006). The importance of research on the exact nature of graph processing in individuals with learning disabilities is specifically emphasized for educational purposes. In the intermediate and secondary grades, graphing has been frequently used to present complex materials and abstract concepts. As a result, lack of graphic comprehension skill has caused students to miss immerse learning of concepts (Parmar & Signer, 2005).

In addition, most previous studies have not examined the effects of subjects' linguistic and cognitive abilities on graph comprehension. To date, researchers studying graph comprehension have focused primarily on characteristics of graphic properties and questioning to determine the interpretation of graphed information. The nearly exclusive focus on graphical properties has limited our understanding of graph processing, particularly, in the population of individuals who have reading disabilities and often rely on contextual cues for comprehension. Furthermore, it is particularly important that subject factors, such as working memory and executive functions, often associated with reading disabilities, thus the factors need be explored for their potential role in graph reasoning(Huang, et al., 2006).

Furthermore, most studies examining learning disabilities have exclusively focused on off-line assessment, such as comprehension measurements. On-line information, such as eye tracking measurements, are beginning to be used more frequently to supplement off-line information by providing moment-by-moment processing information, especially with people who are challenged in the skill of reading (Whitney & Cornelissen, 2007). This study was designed to address whether young adults with dyslexia are impaired in graph comprehension in comparison with their peers without dyslexia by investigating both comprehension accuracy and eye tracking data.

In the current study, the following experimental questions were addressed:

RQ1. How does the performance of college students who have dyslexia compare with their non-dyslexic peers for comprehension accuracy on graph interpretation tasks?

a. It was expected that students with dyslexia would perform more poorly than their peers and that difference would be most prominent on items with the highest level of the graph complexity and the most difficult types of comprehension question.

RQ2. How does the performance of college students who have dyslexia compared with their non-dyslexic peers for response time on graph interpretation tasks?

a. It was expected that the students with dyslexia would be slower than their peers yielding longer eye fixations especially on the more complex graphs and more difficult comprehension questions.

RQ3. If there would be a group effect on response time, where the effect would be driven by?

a. It was expected that the effect would be due to particular parts of the display (e.g., text areas).

RQ4. What is the nature of the relationships between the viewers' performance on tasks of graph comprehension and their cognitive abilities as measures on tasks of vocabulary, working memory, and executive functions?

a. It was hypothesized that vocabulary would not highly correlate with the students' performance on graph comprehension for both groups of participants because the word's level in the stimuli was controlled in terms of difficulty.

b. It was hypothesized that working memory and executive functions would correlate highly with the students' performance on graph comprehension for both groups of participants.

This study has theoretical and practical implications for dyslexia research. First, it will allow us to explore the nature of visual comprehension in students with dyslexia, which has been largely overlooked. Second, it may shed light on how we can support students with reading difficulties when graphs are involved in texts and other reading materials. In this study, we expect to see whether or not we should recommend graphs to dyslexics and whether or not they need explicit and additional instruction for interpreting this kind of information. Educators can use this information to plan what they should focus on for remediating comprehension problems. Thus, this project will provide a foundation for research-based instruction and intervention for comprehension of visual materials.

Study Objectives

The purpose of this study was to explore the effect of reading skill on graph comprehension using combined comprehension accuracy and eye tracking data. A review of the literature review motivated the following two study goals and predictions.

The first goal of this study aimed to establish how students with dyslexia perform on a graph comprehension task compared to typical readers. To achieve this goal, I examined the effects of *graph type* (i.e., line graphs, bar graphs, and horizontal bar graphs), *graph complexity* (i.e., *single* vs. *double* graphic patterns: single line graphs vs. double line graphs, single bar graphs vs. double bar graphs, single horizontal bar graphs vs. double horizontal bar graphs), and *question type* (i.e., questions asked to extract data from a single value vs. questions asked for comparing two values) on their comprehension performance. I predicted that performance would be influenced by the *type of graph* and *task*, and *graph complexity*. Specifically, students with dyslexia will perform less accurately than typical readers on the more complex graphs and on the more complex questions for data interpretation. Also, I expected that dyslexics would show longer eye fixations on graphs, indicating difficulties in search and processing and this difference would become more robust with the increasing complexity of graphs and tasks.

The second goal of this study was to examine the extent to which linguistic and cognitive factors influence comprehension of graphs. For this goal, I examined one linguistic skill (i.e., receptive vocabulary) and two cognitive abilities (i.e., working memory and executive functions) that have been hypothesized to impact dyslexia and investigated relationships between those factors and graph comprehension measured by accuracy and eye movement data. I expected that both working memory and executive functions would have an impact on graph comprehension because of the verbal/visual characteristics of graphs.

CHAPTER 3
METHODS

Introduction

The purpose of this study is to compare response accuracy and eye gaze pattern in young adults with and without dyslexia on different levels of complexity of graph types and graph interpretation questions. College students completed a graph comprehension task while their eye movements were recorded. Reading and reading related skills, working memory, and executive function skills were also assessed. In this chapter, the methods of the study are described.

Methods

Setting and Participants

Two groups of college students aged 18 to 35 years of age were recruited with the approval of the University of Florida Behavioral/NonMedical Institutional Review Board (UFIRB #2011-U-0643): (1) dyslexic group: students who had been diagnosed previously with a specific reading disability or who reported lifelong difficulties with reading, writing, and/or spelling but had not been formally diagnosed with reading disability; (2) typical reading group: students who had no history of neurological or sensory deficits, or speech, language, reading, or general academic problems. Participants were required to be native English speakers.

Recruitment flyers were distributed to University of Florida Disability Resource Center and Santa Fe College Disability Resource Center (Appendix A). Participants were also recruited through the UF LIN-CSD Research Participant Pool website and Educational Research Participant System. The flyers included brief descriptions of the study, benefits from participation, and contact information for potential participants. All participants were compensated in the form of 2 hours of research credit for applicable courses. Specifically, participants with reading disability were provided with a three-page brief report of their test findings when they chose to be informed of their standardized test scores for documentation of their learning disability. Data were collected from August, 2011 through March, 2012.

Participants

A total of forty college students participated in the present study: 17 students with developmental dyslexia and 23 students with typical reading skills.

Written informed consent was obtained from all participants prior to the onset of the research activity (Appendix B). All participants completed a graph familiarity questionnaire about prior experience using graphs (Appendix C). Participants were asked to self-estimate their graph familiarity in graphs on a 7-point scale from 1 (never or strongly disagree) to 7 (very often or strongly agree). To confirm the diagnosis of dyslexia and clarify the classification of two groups, spoken and written language tests were given to all participants. All tests were administered by the author. Participants were diagnosed with developmental dyslexia if they (1) showed deficits on standardized tests of phonological and/or orthographic processing that include phonological awareness, rapid naming, word decoding, word reading, and/or reading fluency unexpected for their other cognitive abilities, educational levels, and socio-cultural opportunities; (2) reported having persistent difficulties and/or remarkable lack of progress in reading, spelling, and/or writing along with a positive family history for reading disabilities; (3) obtained relatively high scores on standardized test of comprehension despite poor word decoding, word recognition, and/or spelling scores; (4) obtained relatively high scores on standardized test of oral language; and (5) had no developmental history of diagnosis and therapy related spoken language impairment with the exception of minor articulation difficulties. Data from 35 participants were used in the final analysis: 15 students with developmental dyslexia and 20 students with normal reading skills. The two groups did not differ significantly in chronological age ($F(1,33) = 2.44$, $p > .05$).

Participants with developmental dyslexia

Among seventeen participants with developmental dyslexia, two students were excluded from the study: (1) One did not meet the age requirement of 18 to 35 years, and (2) the other had difficulty with both spoken and written languages. A total of fifteen college students with developmental dyslexia were included in the final data analysis. A group with dyslexia was 67% female (Male = 5, Female = 10). They ranged in age from 18 to 35 years (Mean = 20.89, SD = 2.69). Table 3-2 shows mean standard scores on the diagnostic reading tests for students with dyslexia.

Participants with typical reading skills

Among twenty three participants who were initially placed into the typical reading control group, three students were excluded from the study for the following reasons: (1) there were technical problems with the eye tracking data of two students, and (2) one student scored below average on the norm-referenced word reading test (TOWRE Test). A total of twenty college students with typical reading skills were included in the final data analysis. A group with normal reading skills was 90% female (Male = 2, Female = 18). They ranged in age from 18 to 35 years (Mean = 19.71, SD = 1.44) . Table 3-3 shows mean standard scores on the diagnostic reading tests for students with normal reading skills.

Data Collection

Procedure

All testing was performed individually in the Language and Cognition Research laboratory in Turlington Hall at the University of Florida. After the author provided general information about the study and the test procedures, the participant was asked to sign two copies of informed consent forms, and then to complete a background/graph questionnaire. One copy of the consent form was given to the participant and the other copy was kept for the researcher's file.

The experimental protocols were administered by the author in approximately 2.5-3 hours. Each subject was completed all tests in the fixed order that follows: (1) general background / graph familiarity questionnaires and questionnaires of a graph familiarity; (2) reading diagnostic session; (3) an experimental session (a graph comprehension assessment); 4) linguistic and cognitive assessments.

Table 3-1. Test measurements used for graph comprehension, language, and cognitive skills

Skill	Name of Test	Subtest
Verbal ability	Woodcock-Johnson III tests of cognitive abilities	Verbal Comprehension
Phonological processing	Comprehensive Test of Phonological Processing	Elision
		Blending Words
		Phonological Awareness Composite
		Memory for Digits
		Nonword Repetition
		Phonological Memory composite
		Rapid Digit Naming
		Rapid Letter Naming
		Rapid Naming Composite
Word reading fluency	Test of Word Reading Efficiency	Sight Word Efficiency
		Phonemic Decoding Efficiency
		Total Word Reading Efficiency
Vocabulary	Shipley vocabulary test	
Working memory	Verbal working memory	Digit forward
		Digit backward
		Digit ordering
	Visual working memory	Block recall
Executive function		Color stroop
		Color-word stroop
		Trail Making A
		Trail Making B
		Digit Symbol Substitution

Instrumentation

A description of the seven psycho-educational tests and the graph interpretation tasks used to test each participants follows. Table 3-1 shows all test measurements used in this study.

Verbal ability assessment

The Picture Vocabulary, Synonyms, Antonyms, and Verbal Analogies subtests from the *Woodcock Johnson III Test of Cognitive Abilities* (WJ-III-COG; Woodcock, McGrew, & Mather, 2002) were administered to assess student's verbal ability. The Picture Vocabulary task required the participant to identify picture of objects. The Synonyms task required the participant to provide a synonym of a given word (e.g., "tell me another word for *car*."). The Antonyms task required participants to create an antonym of a given word (e.g., "tell me the opposite of *floor*."). The Verbal Analogies task required to state a word to complete a two pair analogy (e.g., "*coat* is to *wear* as *apple* is to ____"). Two to three training items were administered prior to each subtest and testing was completed when a student missed three items in a row.

Phonological awareness assessment

The Elision and Blending Words subtests from the *Comprehensive Test of Phonological Processing* (CTOPP; Wagner, Torgesen, & Rashotte, 1999) were administered to assess each participant's phonological awareness skills. The Elision subtest required the participant to listen to and repeat a word, and then say the word without a specified syllable or sound (e.g, "say the word *spider* without saying *der*; say the word *split* without saying /p/). The Blending Words subtest required the participant to put separate sounds together to make a whole word (e.g., "what word do these sound make: t-oi?"). Testing was discontinued when the participant missed three items in a row. The score was recorded as the total number of all items answered correctly. The Phonological awareness composite score derived from the Elision and Blending Words subtest scores.

Phonological memory testing

Memory for digits and Nonword repetition subtests from the *Comprehensive Test of Phonological Processing* (CTOPP; Wagner, et al., 1999) was administered to measure each participant's phonological memory ability. The Memory for digits subtest required the participant to repeat a series of numbers ranging in length from two to eight digits. The Nonword repetition subtest required the participant to repeat a made-up word. Testing was discontinued when the participant missed three items in a row. The score was recorded as the total number of all items answered correctly. The Phonological memory composite score derived from the Memory for digits and Nonword repetition subtest scores.

Rapid automatized naming testing

Rapid number naming and Rapid letter naming subtests from the *Comprehensive Test of Phonological Processing* (CTOPP; Wagner, et al., 1999) were administered to measure each participant's rapid naming ability. The participant was given an 8 x 12 card showing the 6 items in 4 rows of 9 randomly repeated items and asked to name each stimulus item as quickly as possible without making any mistakes. The total time taken to name the stimulus set was timed with a hand-held digital stop watch. The Rapid automatized naming composite score derived from the Rapid number naming and Rapid letter naming subtest scores.

Word reading fluency assessment

The Sight Word Efficiency (SWE) and Phonemic Decoding Efficiency (PDE) subtests from the *Test of Word Reading Efficiency* (TOWRE; Torgesen, Wagner, & Rashotte, 1999) were used to measure each participant's ability to read real and pseudo- words fluently at the single word level. On the each of these subtests, practice items were presented and then the participant was given a series of real (SWE) or pseudo-words (PDE) and asked to read aloud as many as possible in 45 seconds. Inaccurate responses were deducted so that the final score reflected the total number of words correctly read within the given time frame.

Vocabulary assessment

The Shipley vocabulary test (Shipley, 1940) were administered. This multiple choice vocabulary test comprises 40 words, presented in ascending order of difficulty. The developer reported a split-half reliability, in which a test is randomly split into half and scored separately, then the score of one half is compared to the score of the other half (Field, 2009), is .87.

Working memory assessment

To measure Verbal memory ability of the participant, Digit span forward and Digit span backward from the *Wechsler Memory Scale* (Wechsler, 1987) and Digit ordering task (Hoppe, Muller, Werheid, Thone, & von Cramon, 2000) were used. In the Digit span forward measuring verbal short-term memory, the participant repeated verbatim increasingly long lists of numbers. In the Digit span backward measuring verbal working memory, the participant repeated increasingly long lists of numbers in the reverse order of presentation. For the Digit ordering task, the participant was asked to repeat back in numerical order an increasingly long list of digits. To measure the participant's visual working memory ability, Block recall subtest from the *Working Memory Test Battery for Children* (WMTB-C, Pickering & Gathercole, 2001) was used. In the Block recall subtest, participants saw a board with nine cubes, being tapped in random order by the author. The participant was then asked to reproduce the sequence in the correct order by tapping on a picture of the blocks.

Executive function assessment

Color-word Stroop (Golden, 1978), Trails Making (the A and the B versions) (Reitan & Wolfson, 1993), and Digit Symbol Substitution (Wechsler, 1997b) tests were administered to measure the participant's executive function skill. In the Stroop test, measuring inhibition, the participant was asked to name the lists of the color of ink and then name the color of the ink for a series of non-congruent color words. The Trail Making test was used to measure visual attention and switching and consists of two subtest. In the Trails A, the participant was presented with a sheet of paper showing 25 circles numbered 1-25 and asked to draw lines to connect the numbers in ascending order. In the Trails B, circles included numbers and letters. The Participant was asked to connect the circles in the alternating number-letter order of 1-A, 2-B, 3-C, and so forth. In the Digit symbol test measuring a processing speed, the participant was present with a sheet of paper showing nine numbers paired with symbols. The participant was then asked to copy the corresponding symbols in boxes adjoining to the numbers in 90 seconds.

Descriptive statistics for linguistic and cognition measures

As shown in Table 3-4, there was no difference in graphic familiarity between dyslexics and typical readers ($F(1, 33) =.002$, $p>.05$). A main effect for group was found on the vocabulary measure ($F(1, 33) =5.00$, $p<.05$, $\eta_p^2 = .58$) showing that DR had significantly lower scores on the Shipley vocabulary test than TR ($M_{DR}=27.13$, $SD_{DR}=.6.71$, $M_{TR}=31.00$, $SD_{TR}=5.17$). Similarly, the univariate ANOVAs showed significant group effects for all four working memory variables: Digit span forward ($F(1, 33) =7.27$, $p < .05$, $\eta_p^2 = .18$); Digit span backward ($F(1, 33) =4.93$, $p < .05$, $\eta_p^2 = .13$); Digit ordering ($F(1, 33) =11.12$, $p < .01$, $\eta_p^2 = .25$); and Block recall ($F(1, 33) =7.27$, $p < .05$, $\eta_p^2 = .18$). Lastly, the univariate ANOVAs showed group differences for all five executive function variables: Stroop color ($F(1, 33) =10.70$, $p < .01$, $\eta_p^2 = .25$); Stroop word ($F(1, 33) =24.10$, $p < .001$, $\eta_p^2 = .42$); Trail Making A ($F(1, 33) =4.53$, $p < .05$, $\eta_p^2 = .12$); Trail Making B ($F(1, 33) =4.60$, $p < .05$, $\eta_p^2 = .12$); and Digit symbol substitution ($F(1, 33) =18.81$, $p < .01$, $\eta_p^2 = .30$).

Experimental graph comprehension assessment

Experimental graph comprehension test was created using three graph types: (1) line graphs, (2) bar graphs, and (3) horizontal bar graphs and two graphic displays of varying complexity: (1) single graphic displays (2) double graphic displays (i.e., single line vs. double line ; single bar vs. double bar; single horizontal bar vs. double horizontal bar). Each graph was accompanied by two types of questions. The first type of question required the participant to interpret data by examining the intersection of a point on the Y-axis and a point on the X-axis (e.g., How many cats does Harry have?). The second type of questions required the participant to interpret data by comparing values at two points on the graph (e.g., "Does Harry have more cats than dogs"?).

Seventy-two graphs were created based on a study conducted by Ratwani and Trapton (2008) and 72 graphs with double graphic displays (i.e., double line graphs, double bar graphs, and double horizontal bar graphs) were added to create another level of graph complexity. Each graph included the following five major components (Carpenter & Shah, 1998; Renshaw, Finlay, Tyfa, & Ward, 2004). (1) an X-Axis consisting of 3 common objects (e.g., cats, rabbits, dogs); (2) an Y-Axis with numbers ranging from 1 to 10. Each number between 1 and 10 was assigned to each segment in order to ndicate the number of objects that it represented. In the horizontal bar graphs, the axes were reversed; (3) pattern of lines in the line graphs and bars in the bar and the horizontal bar graphs to present the data; (4) legend that informed the participant the referents of graphs features. The legend included two common people's name and coded by different colors; and (5) two types of question that appeared to the right of the graph one by one. For the point locating question, the participant was asked for a literal reading for what a point represents. The answer was one of the ten numbers representing the Y value presented in a given graph. For the comparison question, the participant was asked to compare two data sets represented on the graph and to answer as yes/no. Participants were asked to respond to the questions by pressing one of two buttons and received a score of either 1 (correct answer) or 0 (incorrect answer). The maximum total score was 144. Sample graphs and comprehension questions are shown in Appendices D and E.

Table 3-2. Mean standard scores on the diagnostic reading tests for students with dyslexia

Diagnostic Reading Tests (mean standard score)		Mean	SD	Min	Max
WJ-III-COG	Verbal Comprehension (100)	96.00	13.31	78	119
	Verbal Ability Composite (100)	96.00	13.31	78	119
CTOPP	Elision (10)	7.97	3.65	2	12
	Blending Words (10)	8.05	3.18	4	14
	Phonological Awareness Composite (100)	86.71	18.63	61	115
	Memory for Digits (10)	8.28	2.84	3	13
	Nonword Repetition (10)	7.36	1.15	6	9
	Phonological Memory composite (100)	86.92	9.31	73	103
	Rapid Digit Naming (10)	7.29	2.81	2	11
	Rapid Letter Naming (10)	5.57	2.34	2	10
	Rapid Naming Composite (100)	76.71	15.34	52	100
TOWRE	Sight Word Efficiency (100)	81.50	10.30	67	109
	Phonemic Decoding Efficiency (100)	77.29	8.70	55	95
	Total Word Reading Efficiency (100)	75.21	9.41	53	92

(1) WJ-III-COG: Woodcock Johnson III Test of Cognitive Abilities, (2) WJ-III-ACH: Woodcock-Johnson III Tests of Achievement, (3) CTOPP: Comprehensive Test of Phonological Processing, (4) TOWRE: Test of Word Reading Efficiency
SD: standard deviation, Min: minimum, Max: maximum.

Table 3-3. Mean standard scores on the diagnostic reading tests for students with normal reading skills

Diagnostic Reading Tests (mean standard score)		Mean	SD	Min	Max
WJ-III-COG	Verbal Comprehension (100)	101.55	8.57	85	121
	Verbal Ability Composite (100)	101.55	8.57	85	121
CTOPP	Elision (10)	9.65	2.56	4	12
	Blending Words (10)	10.70	2.18	4	14
	Phonological Awareness Composite (100)	101.05	11.32	70	115
	Memory for Digits (10)	10.80	2.12	7	15
	Nonword Repetition (10)	9.25	1.97	6	13
	Phonological Memory composite (100)	100.15	10.27	82	118
	Rapid Digit Naming (10)	11.20	1.94	6	14
	Rapid Letter Naming (10)	11.00	2.79	6	16
	Rapid Naming Composite (100)	106.60	12.93	76	127
TOWRE	Sight Word Efficiency (100)	101.60	12.17	84	113
	Phonemic Decoding Efficiency (100)	100.65	7.82	90	120
	Total Word Reading Efficiency (100)	101.45	9.25	84	120

(1) WJ-III-COG: Woodcock Johnson III Test of Cognitive Abilities, (2) WJ-III-ACH: Woodcock-Johnson III Tests of Achievement, (3) CTOPP: Comprehensive Test of Phonological Processing, (4) TOWRE: Test of Word Reading Efficiency
SD: standard deviation, Min: minimum, Max: maximum.

Table 3-4. Descriptive statistics for graphic familiarity, linguistic and cognition measures

Measures (maximum scores)	DR Group (N=15)		TR Group (N=20)		*F*-value (1,33)	*p*	Partial η_2	Observed power
	M	SD	M	SD				
Graph familiarity (133)	93.27	17.19	93.08	11.56	.002	.969		
Shipley vocabulary (40)	27.13	6.71	31.00	5.17	5.00	.032*	.131	.582
Working Memory								
Verbal Working Memory								
Digit Span Forward (14)	6.67	1.80	8.35	2.41	7.26	.011*	.180	.744
Digit Span backward (14)	5.60	1.92	7.05	2.31	4.93	.033*	.130	.578
Digit Ordering (24)	13.73	3.43	16.95	2.50	11.12	.002**	.252	.899
Visual Working Memory								
Block Recall (54)	27.27	6.05	31.57	3.57	7.27	.011*	.181	.745
Executive Functions								
Stroop Color (100)	71.00	14.55	84.15	9.82	10.70	.003**	.245	.888
Stroop Word (100)	46.67	9.86	65.00	11.55	24.10	.000***	.422	.997
Trail Making A (sec)	79.93	25.24	65.35	17.75	4.53	.041*	.121	.542
Trail Making B (sec)	94.80	25.60	78.60	19.06	4.60	.039*	.122	.549
Digit Symbol Substitution (93)	62.20	8.18	71.60	8.23	13.81	.001**	.295	.950

M: mean, SD: standard deviation

* $p < .05$, ** $p < .01$, *** $p < .001$

CHAPTER 4
RESULTS

DATA ANALYSIS

All data for demographic characteristics, diagnostic reading assessments, and research questions were analyzed using SPSS version 17.0 for Windows. Results are presented below as they related to each of the research questions followed by a summary of key findings.

Research Question 1: Comprehension Accuracy

The first goal of this study was to investigate how dyslexic readers (DR) perform on a graph comprehension task compared to typical readers (TR). Table 4-1 shows the performance of the two groups on the graph comprehension tasks. A mixed 2 (between subjects - reader type: DR vs. TR) × 3 (within subjects - graph types: *line* vs. *bar* vs. *horizontal bar* graphs) × 2 (within subjects - graphic display: *single* vs. *double* graphic displays) × 2 (within subjects - question types: *point locating* vs. *comparison* questions*)* analysis of variance (ANOVA) and post-hoc Bonferroni-corrected pairwise comparisons were used to examine whether any significant differences exist in graph comprehension accuracy between young adult with DR and TR age-matched controls.

This four-way ANOVA yielded significant findings for (1) four main effects, (2) two two-way interactions, and (3) one three-way interactions. A summary of results is shown in Table 4-2. ANOVAs with within-subject variables were calculated under the assumption of sphericity, a condition where the variances of the differences between levels of the within-subject variables are equal. Mauchly's test (Maunchly, 1940) result indicated that the assumption of sphericity has not been violated (all p >.05). Therefore, sphericity-assumed F-values were reported for all measures. Total number of correct response for each of the graph interpretation questions (12 items per each condition) was used for data analysis. Effect sizes, using partial eta square, were also reported to evaluate the size of mean differences. Cohen (1988) characterized the value of partial eta squared of .01 as small, .06 as moderate, and .14 as a large effect size.

Significant main effects were found for all variables: group, graph type, question type, and graphic display pattern. Although differences in mean performance on comprehension accuracy were very small, DR were significantly less accurate in interpreting graphs than TR (M_{DR} = 11.33, SE_{DR} = .064, M_{TR} = 11.56, SD_{TR} = .056; $F(1,33) = 7.28$, p=.011, $\eta_p^2 = .181$). Significant differences in comprehension accuracy were found for graph types (M_{line} = 11.60, SE_{line} = .056, M_{bar} = 11.54, SD_{bar} = .058; $M_{horizontal\ bar}$ = 11.20, $SE_{horizontal\ bar}$ = .060, $F(2,32) = 19.87$, $p < .001$, $\eta_p^2 = .376$). Bonferroni-corrected pairwise comparisons between the three graph types revealed that all participants were less accurate on horizontal bar graphs items than on line graphs ($p < .001$) or bar graph items ($p < .001$). Similarly, all participants were less accurate in interpreting graphs with double graphic displays than those with single graphic displays (M_{single} = 11.63, SD_{single} = .053; M_{double} = 11.27, SE_{double} = .058, $F(1,33) = 25.85$, $p < .01$, $\eta_p^2 = .439$). Again, all participants were less accurate in interpreting graphs presented with comparison questions than graphs with point locating questions ($M_{Point\ locating}$ = 11.68, $SD_{Point\ locating}$ = .033; $M_{comparison}$ = 11.22, $SE_{comparison}$ = .066, $F(1,33) = 55.80$, $p < .001$, $\eta_p^2 = .628$).

The ANOVA revealed two significant two-way interactions: group × question type and graph type × graphic display. First, a significant interaction between group and question type was found ($F(1,33) = 9.08$, $p < .01$, $\eta_p^2 = .214$). To interpret the nature of the interactions, each main effect (group) at different levels of the second main effect (question type) was compared, using Bonferroni correlations to control for alpha inflation. For the comparison question type, DR were significantly less accurate than TR (t (33) = 3.11, $p < .01$). However, group difference was not found for the point locating question type ($p > .05$). Thus, dyslexic readers' comprehension decreased when the complexity of question increased. Figure 4-1displays graphical representations of this information.

Further, a significant interaction for graph type × graphic display ($F(2,32) = 23.91$, $p < .001$, $\eta_p^2 = .599$) was found. The interaction was explored by comparing the comprehension accuracy between line, bar, and horizontal bar graph across graphic display (single and double). Participants' comprehension accuracy for horizontal bar graphs was significantly lower than comprehension accuracy for line (t (32) = 7.25, $p < .001$) or bar graphs (t (32) = 8.57, $p < .001$) on the double graphic display. This pattern was not found on the single graphic display (all $p > .05$). This interaction reveals that when the complexity of graph increased, participants have more difficulty processing horizontal graphs compared to line or bar graphs. Figure 4-2 displays graphical representations of this information.

Lastly, one significant three-way interaction was found for group × graph type × question type ($F(2,32) = 5.94$, $p < .01$, $\eta_p^2 = .271$). The interaction was explored by comparing the comprehension accuracy between groups across question types (i.e. point locating and comparison) in each graph type (i.e., line, bar, and horizontal bar graphs). The finding indicates that the group and question type interaction was different across graph types (i.e., line, bar and horizontal bar graphs). Specifically, in the line (t (32) = 3.70, $p < .01$) and the bar graphs (t (32) = 2.53, $p < .05$), DR responded less accurately than TR for comparison questions, while there was no significant difference between the two groups for point locating questions (all $p > .05$). In contrast, for the horizontal bar graphs, this pattern was not found (all $p > .05$). Figure 4-3 displays graphical representations of this information.

Table 4-1. Descriptive statistics for DR and TR groups on graph accuracy

Measures (milliseconds)		DR Group (N=15)				TR Group (N=20)			
		Point locating question		Comparison question		Point locating question		Comparison question	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Line graph									
	Single pattern	12.00	.00	11.20	.68	11.85	.49	11.75	.55
	Double pattern	11.98	.26	10.67	1.23	11.75	.44	11.65	.81
Bar graph									
	Single pattern	11.87	.35	10.93	.96	11.85	.37	11.50	.76
	Double pattern	11.47	.74	11.33	.72	11.80	.52	11.60	.60
Horizontal bar graph	Single pattern	11.87	.52	11.47	.74	11.85	.37	11.35	.99
	Double pattern	10.80	.41	10.47	.64	11.10	.31	10.47	.571

M: mean, SD: standard deviation, Min: minimum, Max: maximum

Table 4-2. Summary of mixed four way ANOVA on comprehension accuracy measures

Effects		F-value	p	Partial η^2	Observed power
Main Effects	Group	$F(1,33) = 7.28$ (A)	.011*	.181	.745
	Graph type	$F(2, 32) = 19.87$ (A)	.000***	.376	1.00
	Question type	$F(1,33) = 55.80$ (A)	.000***	.628	1.00
	Graphic display	$F(1,33) = 25.85$ (A)	.001**	.439	1.00
Two-way Interaction	Group x Graph type	$F(2,32) = 1.33$ (A)	.272	.039	.278
	Group x Question type	$F(1, 33) = 9.08$ (A)	.005**	.214	.830
	Group x Graphic display	$F(1,33) = .072$ (A)	.663	.006	.071
	Graph type x Question type	$F(2,32) = .815$ (A)	.447	.024	.184
	Graph type x Graphic display	$F(2,32) = 23.91$(A)	.000***	.599	1.00
	Question type x Graphic display	$F(1,33) = 2.85$ (A)	.101	.079	.374
Three-way Interaction	Group x Graph type x Question type	$F(2,32) = 5.94$ (A)	.006**	.271	.887
	Group x Graph type x Graphic display	$F(2,32) = 1.54$(A)	.220	.045	.318
	Group x Question type x Graphic display	$F(1,33) = 2.01$ (A)	.116	.057	.280
	Graph type x Question type x Graphic display	$F(2,32) = .898$ (A)	.412	.026	.199
Four-way Interaction	Group x Graph type x Graphic display x Question type	$F(2,32) = .719$ (A)	.491	.021	.167

A: Sphericity-assumed F-values, B: Greenhouse-Geisser corrected F-values

* $p < .05$, ** $p < .01$, *** $p < .001$

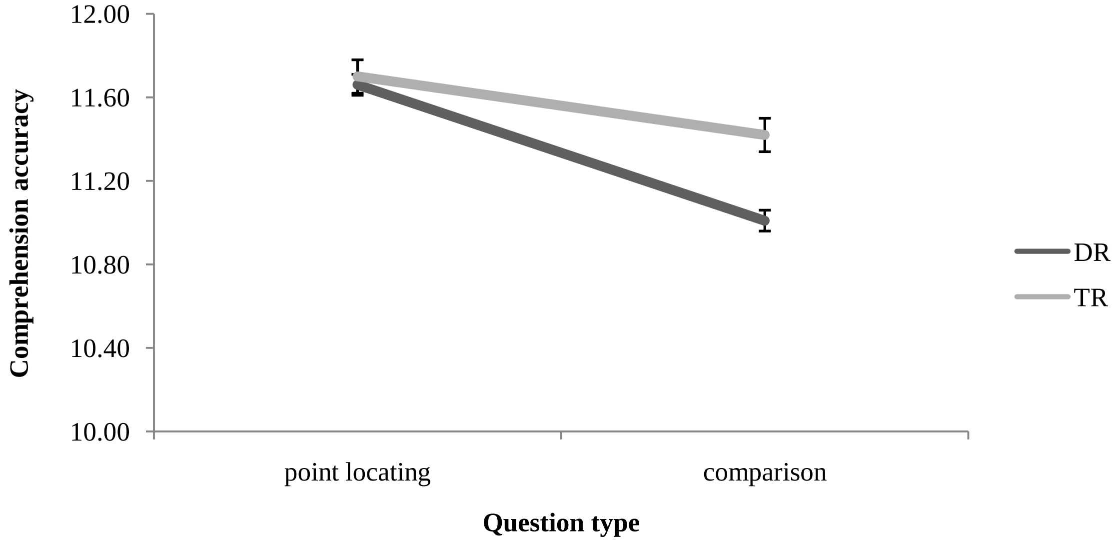


Figure 4-1. Two-way interaction between question type and group

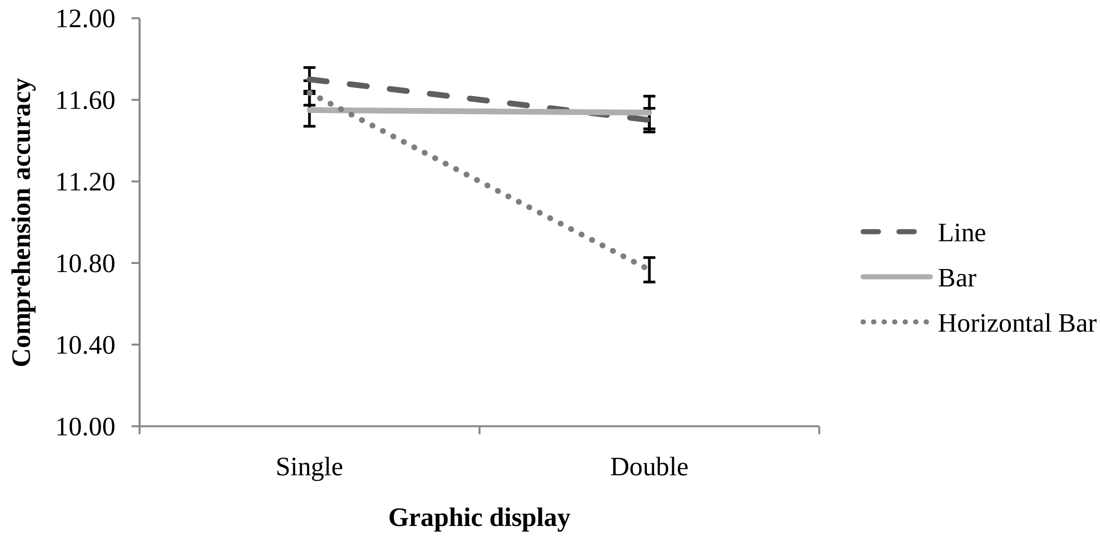


Figure 4-2. Two-way interaction between graphic display and graph type

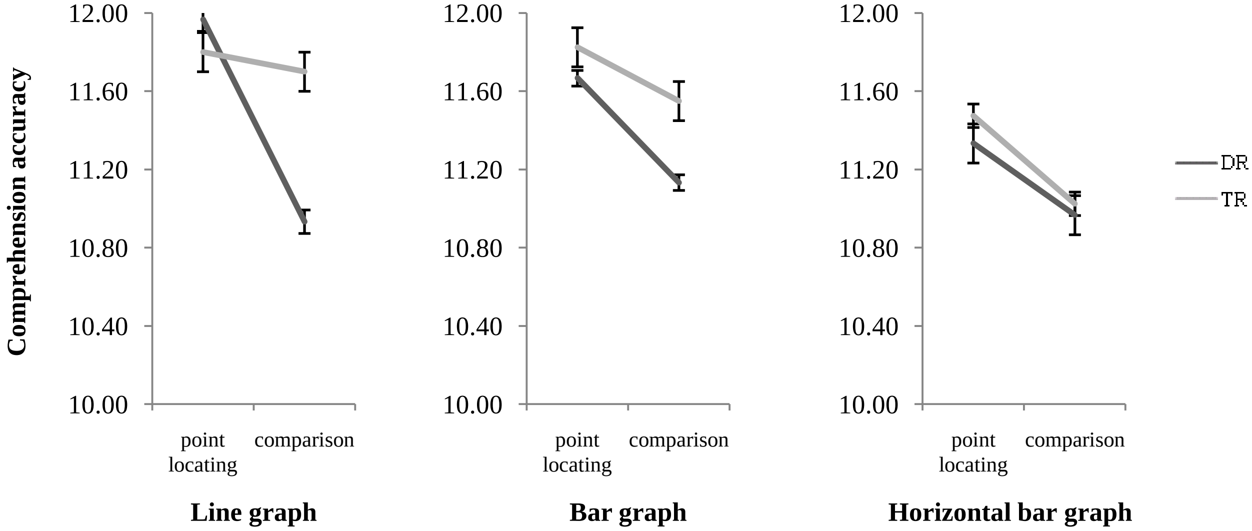


Figure 4-3. Three-way interaction between graph type, question type, and group

Research Question 2: Eye Tracking Data Analysis

The second goal of this study was to compare eye gaze data of DR and TR to see whether their performance would be influenced by graph type, graphic display, and question type. The overall viewing times (i.e., whole trial times) were analyzed using a mixed 4-way multivariate analysis of variance (ANOVA), with group (i.e., DR vs. TR) as a between-subject factor and graph type (i.e., *line* vs. *bar* vs. *horizontal bar* graph), graphic display (i.e., *single* vs. *double*), and question type (i.e., *point location* vs. *comparison* questions) as within-subject factors. Post-hoc pairwise comparisons using Bonferroni corrections to control for alpha inflation were conducted to interpret main and interaction effects. Table 4-3 shows the overall viewing times of the two groups on the graph comprehension tasks.

The four way ANOVA yielded significant findings on overall viewing time for (1) four main effects, (2) three two-way interactions, and (3) one three-way interaction. These ANOVA results are shown in Table 4-4. Within-subject variables were calculated under the assumption of sphericity, a condition where the variances of the differences between levels of the within-subject variables are equal. Mauchly's test indicated that the assumption of sphericity has been violated in graph type x graphic display interaction and group x graph type x graphic display x question type interaction ($p < .05$). Thus, relatively conservative Greenhouse-Geisser corrected *F*-values were reported for the two interactions.

Significant main effects were found for all variables: group, graph type, graphic display, and question type. DR viewed graphs for significantly longer time than TR ($M_{DR} = 7197.04$, $SE_{DR} = 352.07$; $M_{TR} = 5371.79$, $SD_{TR} = 304.90$; $F(1,33) = 15.36$, $p < .001$, $\eta_p^2 = .318$). Viewing times were different depending on graph type ($M_{line} = 6411.39$, $SE_{line} = 240.70$, $M_{bar} = 6128.15$, $SD_{bar} = 232.21$; $M_{horizontal\ bar} = 6313.72$, $SE_{horizontal\ bar} = 240.29$, $F(2,32) = 5.98$, $p < .01$, η_p^2

= .266). Bonferroni-corrected pairwise comparisons between three graph types revealed that all participants spent a significantly longer time processing line graphs than bar graphs (t (32) = 3.23, $p < .01$). There was no time differences between line and horizontal bar graphs ($p > .05$). Similarly, all participants spent significantly longer time in processing graphs with double graphic displays than graphs with single graphic displays (M_{single} = 5359.68, SE_{single} = 193.70; M_{double} = 7209.16, SE_{double} = 280.88, $F(1,33) = 215.06$, $p < .001$, $\eta_p^2 = .867$). Finally, all participants spent significantly longer time in processing graphs with comparison questions than graphs with point locating questions ($M_{Point\ locating}$ = 5527.88, $SE_{Point\ locating}$ = 204.56; $M_{comparison}$ = 7040.96, $SE_{comparison}$ = 269.01, $F(1,33) = 198.97$, $p < .001$, $\eta_p^2 = .858$).

The ANOVA revealed three significant two-way interactions: group × question type, group × graphic display, and question type × graphic display. First, a significant interaction between group and question type was found ($F(1,33) = 9.46$, $p < .01$, $\eta_p^2 = .223$). To interpret the nature of the interactions, each main effect at different levels of the second main effect, using Bonferroni correlations to control for alpha inflation, was examined. For both groups, the overall viewing times for comparison questions were significantly longer than for point locating questions (t (33) = 11.37, $p < .001$ for DR, t (33) = 8.45, $p < .001$ for TR); however, the overall viewing times in the two question types showed a greater difference in DR group rather than in TR group, as shown figure 4-4. This finding suggests that time dyslexic readers spent to process graphs significantly increased when the complexity of question increased.

Further, a significant interaction between group and graphic display was found ($F(1,33) = 4.95$, $p < .05$, $\eta_p^2 = .131$). The interaction was analyzed by using Bonferroni correlations to control for alpha inflation. For both groups, the overall viewing times for graphs with double displays were significantly longer than for graphs with single displays(t (33) = 11.21, $p < .001$

for DR and t (33) = 3.99, $p < .01$ for TR); however, the overall viewing times in the two graphic displays showed a greater difference in DR group rather than in TR group, as shown figure 4-5. This finding suggests that time dyslexic readers spent to process graphs significantly increased when the complexity of graphic displays increased.

Lastly, a significant interaction for graphic display × question type (F(1,33) = 17.04, $p < .001$, $\eta_p^2 = .341$) was found. To interpret the nature of the interactions, each main effect at different levels of the second main effect was examined, using Bonferroni correlations to control for alpha inflation. For both graphic displays, the overall viewing times for graphs with comparison questions were significantly longer than for graphs with point locating questions (t (32) = 12.08, $p < .001$for single displays and t (32) = 17.16, $p < .001$for double displays); however, the overall viewing times in the two question types showed a greater difference for double graphic displays rather than for single graphic displays, shown figure 4-6.

The ANOVA also yielded one significant three-way interaction for graph type x graphic display x question type (F(2,32) = 6.00, $p < .01$, $\eta_p^2 = .154$). The interactions between graphic display and question type were compared at each type of graph (line, bar, and horizontal bar graphs). In the line graph, the viewing time difference between single and double graphic displays was significantly larger in graphs with comparison questions than graphs with point locating questions (t (32) = 4.64, $p < .001$). That is, participants needed significantly longer time to process double graphic graphs with comparison questions. Similarly, in the bar graph, the viewing time difference between the two graphic displays were significantly larger in the comparison question condition than in the point locating question condition (t (32) = 3.46, $p < .01$). However, this different pattern between single and double graphic displays across types of questions was not found in the horizontal graphs. Figure 4-7 displays graphical representations of this information.

Table 4-3. Descriptive statistics for DR and TR groups on overall viewing times

Measures (milliseconds)		DR Group (N=15) Point locating question Mean	SD	Comparison question Mean	SD	TR Group (N=20) Point locating question Mean	SD	Comparison question Mean	SD
Line graph									
	Single pattern	5733.73	1317.12	6832.47	1226.65	4187.40	1122.98	5134.03	1217.07
	Double pattern	7195.24	1180.96	9616.16	2069.06	5500.63	1373.14	7091.42	2464.90
Bar graph									
	Single pattern	5063.78	1102.89	6905.02	1470.64	3881.83	1112.15	4928.30	1417.46
	Double pattern	6950.64	1093.74	9275.73	1783.54	5337.07	1600.95	6682.80	2044.42
Horizontal bar graph	Single pattern	5299.16	916.96	6957.64	1099.43	4210.68	1203.55	5182.12	1540.36
	Double pattern	7410.56	2044.69	9124.40	1861.74	5563.85	1410.35	6761.37	2011.84

M: mean, SD: standard deviation

Table 4-4. Summary of mixed four way ANOVA on overall viewing time measures

Effects		*F*-value	*p*	Partial η^2	Observed power
Main Effects	Group	$F(1,33) = 15.36$ (A)	.000***	.318	1.00
	Graph type	$F(2,32) = 5.98$(A)	.005**	.266	.867
	Question type	$F(1,33) = 198.97$(A)	.000***	.858	1.00
	Graphic display	$F(1,33) = 215.06$ (A)	.000***	.867	1.00
Two-way Interaction	Group x Graph type	$F(2,32) = .186$ (A)	.831	.006	.078
	Group x Question type	$F(1, 33) = 9.46$ (A)	.004**	.223	.847
	Group x Graphic display	$F(1,33) = 4.95$ (A)	.033*	.131	.579
	Graph type x Question type	$F(2,32) = 1.20$ (A)	.308	.035	.253
	Graph type x Graphic display	$F(1.69,55.08) = .19$ (B)	.824	.006	.079
	Question type x Graphic display	$F(1,33) = 17.04$ (A)	.000*	.341	.980
Three-way Interaction	Group x Graph type x Question type	$F(2,66) = .774$ (A)	.466	.023	.176
	Group x Graph type x Graphic display	$F(2,66) = .194$ (A)	.824	.006	.079
	Group x Question type x Graphic display	$F(1,33) = .888$ (A)	.353	.026	.150
	Graph type x Question type x Graphic display	$F(2,32) = 6.00$ (A)	.004**	.154	.868
Four-way Interaction	Group x Graph type x Graphic display x Question type	$F(1.90,62.84) = 1.47$ (B)	.240	.042	.301

A: Sphericity-assumed *F*-values, B: Greenhouse-Geisser corrected *F*-values
* $p < .05$, ** $p < .01$, *** $p < .001$

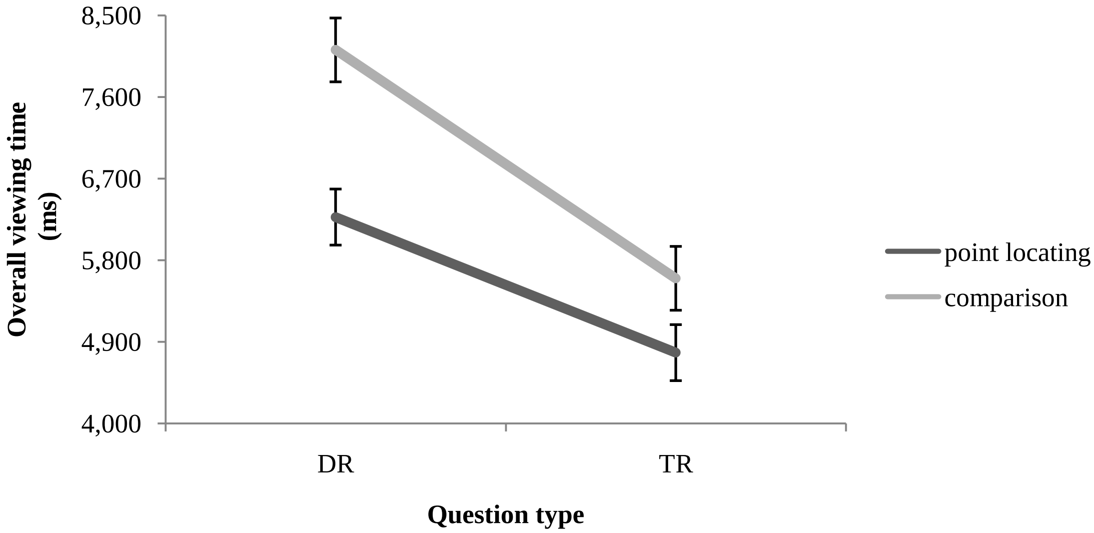


Figure 4-4. Two-way interaction between question type and group

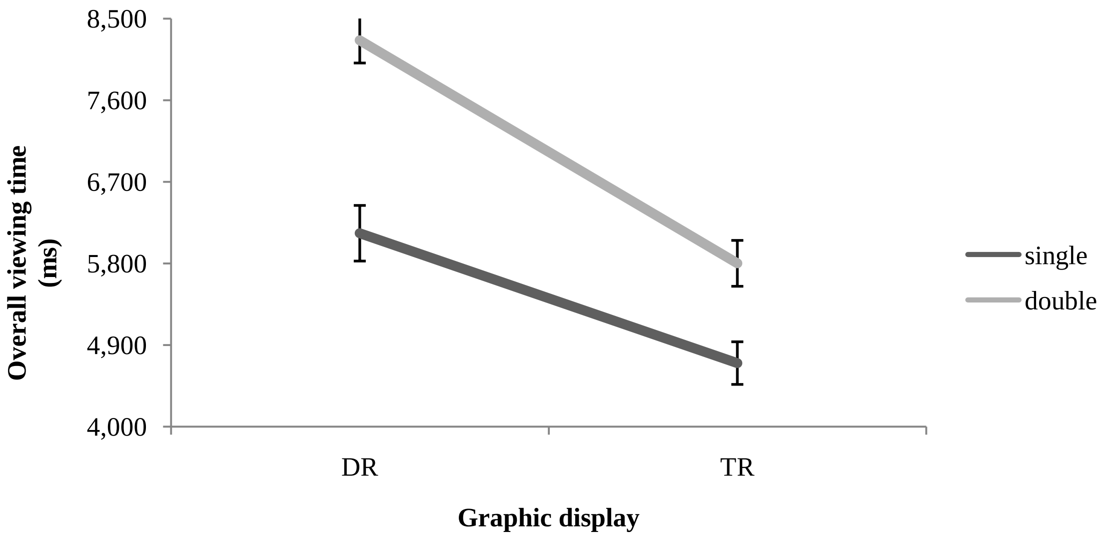


Figure 4-5. Two-way interaction between graphic display and group

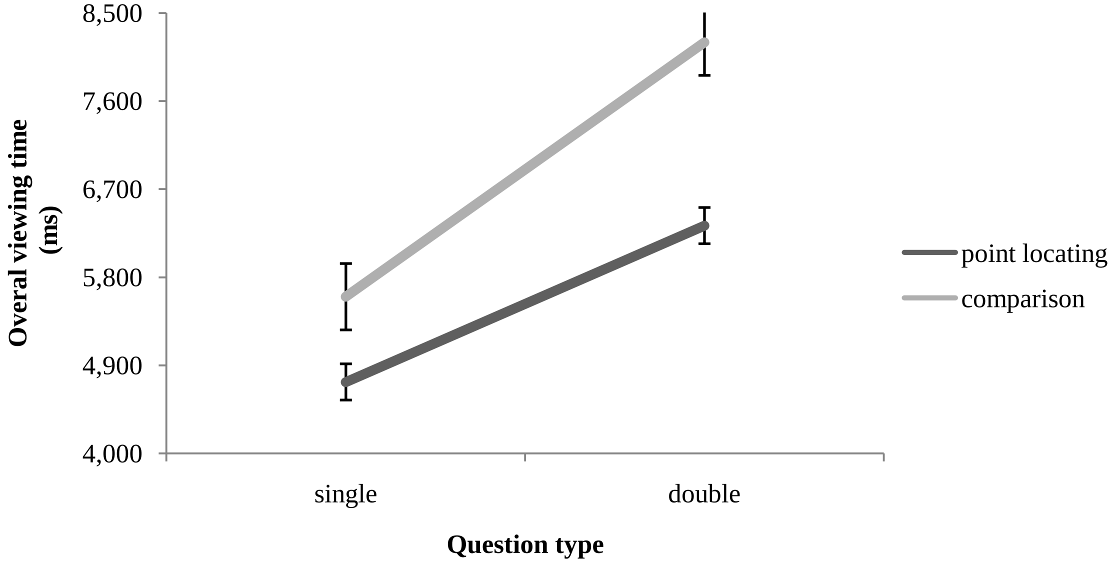


Figure 4-6. Two-way interaction between question type and graphic display

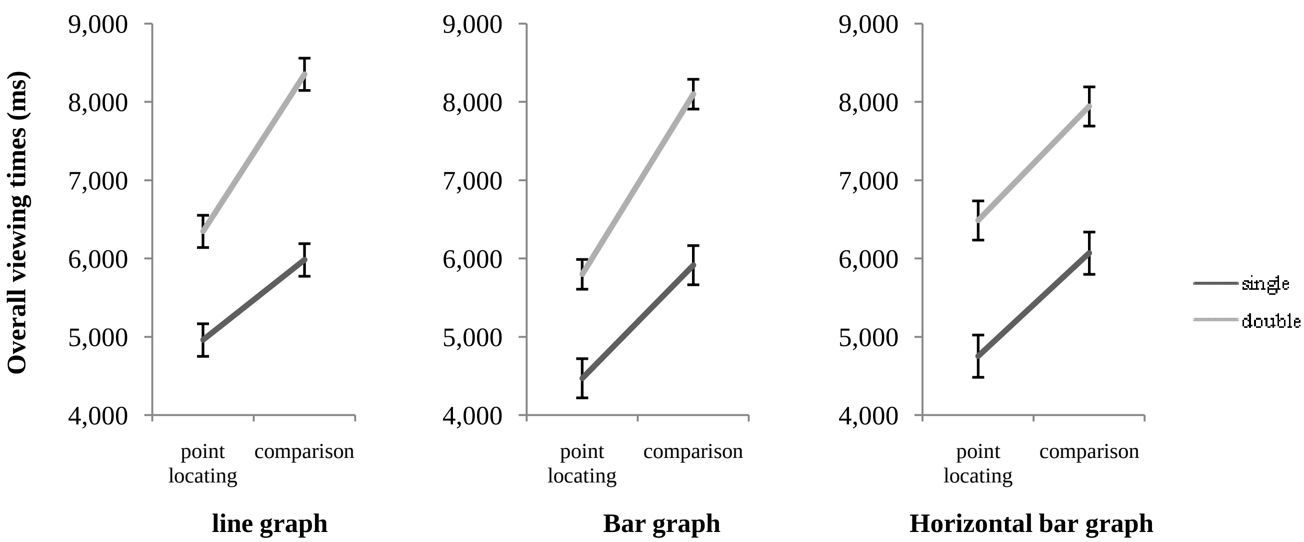


Figure 4-7. Three-way interaction between graphic display, question type, and graph type

Research Question 3: Eye Tracking Data Analysis II

DR took longer to visually process this information overall. The following question was whether this effect would be driven by particular parts of the display or is due to longer looking times at all of the parts of the display. The third goal of this study was to compare eye gaze data of DR and TR in order to determine viewing times differ for specific six graphic subregions (i.e., pattern, x-axis, y-axis, legend, question, answer).

A schematic of these subregion is shown in figure 4-8. A multivariate analysis of variance (MANOVA) and subsequent univariate analyses of variances (ANOVAs) were conducted, using Bonferroni's adjustment to control Type 1 error rates associated with multiple comparisons.

Table 4-5 shows the performance of the two groups in two standard time measures of eye gaze which have been adapted from key measures of reading text without graphs (i.e., first pass time and total viewing time). According to Filik et al. (2005) and Hutzler & Wimmer (2004), first pass time is the sum of all fixations in a region of the sentence prior to exiting that region and total viewing time is the sum of all fixations in a region. In reading research, regression path time is one of the key eye tracking measures. However, the regression path time was excluded in this study because the regression path method (i.e., looking back at text) was developed for examining text reading. Given that information on a graph is not likely to be viewed in the linear manner as in reading text, the use of this procedure has no intrinsic value for graph interpretation.

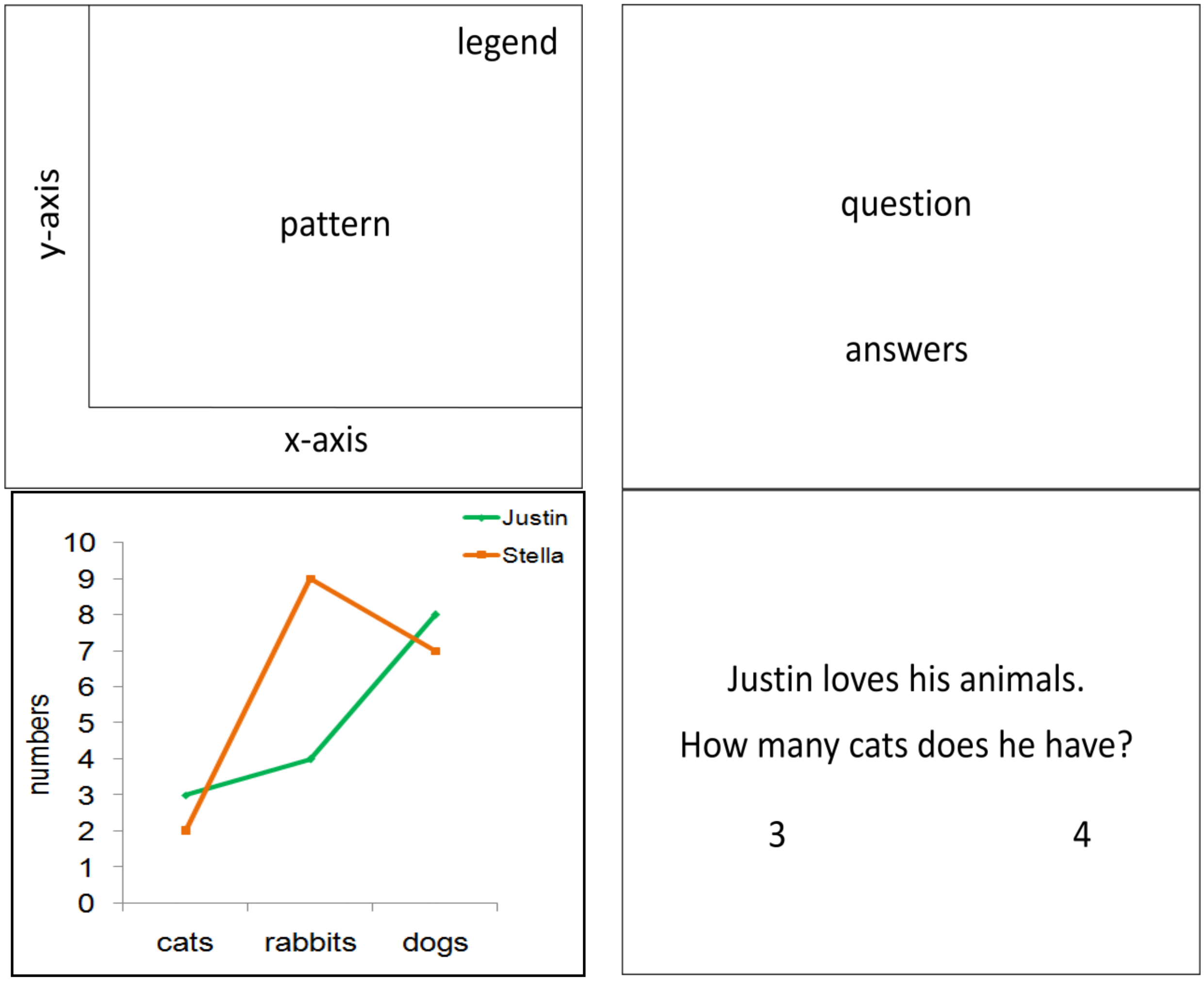


Figure 4-8. Six regions of the display: pattern, X-Axis, Y-Axis, legend, question, and answer

Three assumptions for MANOVA were checked prior to the analysis: (1) multivariate normal distribution, (2) homogeneity of covariance matrices, and (3) homogeneity of error variance. First, to check the multivariate normal distribution, skewness and kurtosis of dependent variables were calculated. For the first pass time, skewness and kurtosis values for all regions except graph pattern fell within the range of – 1 to + 1. For the total viewing time, the values for all regions fell within the range of – 1 to + 1. The skewness and kurtosis values of 2 out of 18 variables were outside of the ± 1 range, which may indicate the violation of normality. However, the Multivarite *F* test is robust in accounting for non-normality, if the non-normality is caused by skewness or kurtosis (French, Macedo, Poulsen, Waterson, & Yu, 2008). For the second assumption, homogeneity of covariance matrices, Box's M tests (Box, 1949) for the homogeneity of variance-covariance matrices across design cells were estimated. This assumption is especially important for unbalanced designs (i.e., unequal number in each group). Box's M tests were not significant for both viewing time measures at the p=.001 level: first pass time (F(45, 2995.10)=.778, p>.001) and total viewing time (F(45, 2995.10) = 1.51, p > .001). These findings indicate that the assumption of homogeneity of the variance covariance matrix of dependent variables across design cells was not violated. For the third assumption, homogeneity of variance, Levene's tests (Levene, 1953, 1960) were conducted for each of the reading time measures. None of the variables had significant F value (p < .001). Thus, the assumption of homogeneity of variance is supported for all variables. In the most cases, the three assumptions for using the MANOVA were not violated, however, because of the limited number of participants, the relatively conservative Pilla's trace statistic was used to estimate the multivariate F statistical inference.

For both measures, DR spent significantly longer time than TR. Specifically, first pass times (F(1, 33) = 12.79, p< .01, η_p^2 = .28) and total viewing times (F(1, 33) = 21.07, p < .001, η_p^2 = .39) were reliably longer for DR than for TR. Next, multivariate analysis of variance (MANOVA) and subsequent univariate analyses of variances (ANOVAs) were conducted to compare first pass times and total viewing times on each subregion (i.e., pattern, x-axis, y-axis, legend, question, answer). The analyses for graphics (pattern, x-axis, y-zaix and legend) and for text (question and answer) were conducted separately to investigate the etiology of group differences.

As shown in Table 4-6, in the graphic areas, a main effect for group was not found for first pass times ($F(4,30) = 1.38$, $p > .05$, $\eta_p^2 = .01$). The following univariate ANOVA also did not reveal any significant group effect. In contrast, in the text areas, a main effect for group was found for first pass times ($F(2,32) = 11.29$, $p < .001$, $\eta_p^2 = .41$). Thus, univariate ANOVAs were used to examine which dependent variables were affected by group. Significant main effects were found for both subregion variables, question ($F(1, 33) = 17.23$, $p < .001$, $\eta_p^2 = .34$) and answer ($F(1, 33) = 12.08$, $p < .01$, $\eta_p^2 = .268$). The effect sizes suggest moderate to large effects for eye gaze on subregion variables with the largest effect for the question subregion.

As shown in Table 4-7, the multivariate analyses of variance for total viewing times of graphics and text were also conducted separately. In the graphics, multivariate analysis of variance, there was no significant main effect for group ($F(4, 30) = 2.52$, $p >.05$, $\eta_p^2 = .25$) because there was only one significant univariate main effect, for pattern ($F(1, 33) = 6.82$, $p < .05$, $\eta_p^2 = .171$). In contrast, the multivariate analysis of variance for total viewing time for text regions showed significant main effects for group ($F(2, 32) = 16.66$, $p < .001$, $\eta_p^2 = .51$). Using univariate ANOVAs, significant main effects were found for both dependent variables: question ($F(1, 33) = 26.25$, $p < .001$, $\eta_p^2 = .443$); and answer ($F(1, 33) = 6.29$, $p < .05$, $\eta_p^2 = .16$). The effect sizes suggest moderate to large effects of total viewing time with the largest effect shown for the question variable.

Table 4-5. Descriptive statistics for DR and TR groups reading times on each graphic region

	DR Group (N=15)				TR Group (N=20)			
Measures (millisecond)	M	SD	Min	Max	M	SD	Min	Max
First Pass Time								
X-axis	439.03	85.27	329.40	661.08	446.07	86.95	324.50	655.43
Y-axis	205.16	53.31	107.52	288.26	162.56	74.18	25.20	308.49
Pattern	275.34	98.70	188.24	515.43	273.37	75.95	191.06	460.45
Legend	440.50	59.56	334.00	563.34	456.74	78.42	340.57	612.40
Question	2224.89	398.64	1484.21	2864.03	1633.06	430.67	935.86	2459.97
Answer	420.68	96.43	273.37	636.79	329.19	48.87	188.32	428.26
Total Viewing Time								
X-axis	654.35	200.41	339.40	1074.72	611. 78	206.95	282.83	971.42
Y-axis	294.92	41.53	227.14	386.18	296.16	60.72	218.93	450.52
Pattern	917.05	307.46	453.74	1413.54	705.83	166.46	455.32	1108.82
Legend	760.10	124.68	471.27	974.63	654.62	178.38	446.11	1112.11
Question	3783.86	593.49	2545.48	4734.54	2476.39	842.57	1392.89	4795.48
Answer	490.38	68.29	321.25	604.95	431.27	59.09	312.97	543.34

M: mean, SD: standard deviation, Min: minimum, Max: maximum

Table 4-6. Summary of between multivariate analysis of variance on interest areas of first pass times

	F-value	*p*	Partial η^2	Observed power
Graphics	$F(4,30) = 1.38$	.967	.018	.075
X-axis	$F(1,33) = .06$	.812	.002	.056
Y-axis	$F(1,33) = .01$	.946	.000	.050
Pattern	$F(1, 33) = .00$	.957	.000	.050
Legend	$F(1,33) = .45$	.508	.013	.100
Text	$F(2,32) = 11.29$	.000***	.414	.987
Question	$F(1, 33) = 17.23$	.000***	.343	.981
Answer	$F(1,33) = 6.29$	.017*	.160	.682

* $p < .05$, ** $p < .01$, *** $p < .001$

Table 4-7. Summary of between multivariate analysis of variance on interest areas of total viewing times

	F-value	*p*	Partial η^2	Observed power
Graphics	$F(4, 30) = 2.52$	.06	.252	.642
X-axis	$F(1,33) = .31$	.55	.01	.091
Y-axis	$F(1,33) = 3.56$	.07	.10	.45
Pattern	$F(1, 33) = 6.82$	.013*	.171	1.00
Legend	$F(1,33) = 3.83$	.059	.104	.476
Text	$F(2,32) = 16.664$	.000***	.510	.999
Question	$F(1, 33) = 26.25$	.000***	.443	1.00
Answer	$F(1,33) = 12.08$	.001**	.268	.921

* $p < .05$, ** $p < .01$, *** $p < .001$

Research Question 4: Correlation among Graph Comprehension and Language and Cognition Measures

Pearson's correlation coefficients were used to measure the strength of the relationships among comprehension accuracy, graphic (including x-axis, y-axis, legend, and pattern) viewing time, text (including question and answer) viewing time, receptive vocabulary, working memory, and executive function performance, as shown in tables 4-8 and 4-9. The significance level for these calculations was set at $p < .05$ (two-tailed).

For DR, comprehension accuracy did not correlate significantly with any language or cognition measures (all $p > .05$). The graphic viewing time correlated significantly with two working memory measures (Digit forward: $r = -.561$, $p < .05$, Block recall: $r = -.541$, $p < .05$) and one executive function measure (Digit Symbol Substitution: $r = -.528$, $p < .05$). The text viewing time correlated with three verbal working memory measures (Digit forward: $r = -.647$, $p < .01$, Digit backward: $r = -.610$, $p < .05$, Digit ordering: $r = -.577$, $p < .05$) and one executive function measure (Stroop-word: $r = -.536$, $p < .05$).

For TR, comprehension accuracy correlated significantly with three executive function measures (Stroop-word: $r = -.592$, $p < .01$, Trails A: $r = -.447$, $p < .05$, Trails B: $r = -.563$, $p < .01$). The graphic viewing time correlated significantly with one working memory measure (Block recall: $r = -.551$, $p < .05$) and two executive function measures (Stroop-word: $r = -.738$, $p < .01$, Digit Symbol Substitution: $r = -.545$, $p < .05$). The text viewing time correlated significantly with one working memory (Block recall: $r = -.550$, $p < .05$), and one executive function measure (Stroop-word: $r = -.521$, $p < .05$).

Table 4-8. Students with dyslexia: correlations between comprehension accuracy, viewing times and cognition measures

	Vocabulary	Working Memory				Executive Function				
	Shipley	Digit forward	Digit backward	Digit ordering	Block recall	Stroop Color	Stroop Word	Trails A	Trails B	Digit Symbol Substitution
Comp. accuracy	.293	.173	.313	.042	.285	.046	.141	-.223	-.078	.264
Graphic viewing time	-.096	-.561*	-.050	-.042	-.541*	-.041	-.346	.246	.378	-.528*
Text viewing time	.209	-.647**	-.610*	-.577*	-.346	-.104	-.536*	.424	.051	-.212

Table 4-9. Typical readers: correlations between comprehension accuracy, viewing times and cognition measures

	Vocabulary	Working Memory				Executive Function				
	Shipley	Digit forward	Digit backward	Digit ordering	Block recall	Stroop Color	Stroop Word	Trails A	Trails B	Digit Symbol Substitution
Comp. accuracy	-.222	.067	-.068	.052	.434	.326	.592**	-.447*	-.563**	.052
Graphic viewing time	-.418	-.372	.092	-.031	-.551*	-.020	-.738**	.406	.409	-.545*
Text viewing time	-.159	-.391	.037	-.037	-.550*	.105	-.521*	.039	.336	-.041

* $p < .05$, ** $p < .01$, *** $p < .001$
Comp.: comprehension
Graphic viewing times: viewing times for x-axis, y-axis, pattern, and legend
Text viewing times: viewing times for question and answer

Summary of Findings

A summary of the comparative data for DR and TR on graph interpretation accuracy, graph interpretation processing time, and correlations between graph comprehension variables, vocabulary, working memory, and executive functions is shown below.

Results for questions 1 and 2 (the comprehension accuracy and eye tracking data) are as follows: (1) Students with dyslexia performed less accurately and more slowly than typical readers on interpreting graphs; (2) Participants overall performed less accurately and more slowly for graphs associated with double graphic displays than for graphs with single graphic displays; (3) Participants performed less accurately and more slowly for graphs presented with comparison questions than for graphs with point locating questions; (4) Participants were most accurate and efficient in answering questions associated with bar graphs. For the line graphs, participants were as accurate as for the bar graphs; however, they spent greater time processing the line graphs than the bar graphs. Participants were least accurate and spent the longest amount of time processing the horizontal bar graphs; (5) For both comprehension accuracy and viewing times, there was a significant group and question type interaction effect. Dyslexic participants took significantly longer to process graphs associated with comparison questions than typical readers. This finding suggests that dyslexics were more influenced by the complexity of the question than typical readers; (6) For the viewing times, there was a significant group and graphic display interaction effect. Dyslexic readers spent significantly more time viewing graphs associated with double graphic displays (i.e., more difficult questions) than typical readers. Again, this finding suggests that the complexity of the graph influenced dyslexics more than typical readers; (7) There was no interaction between the group and the graph types for either comprehension accuracy or viewing times. That is, dyslexic subjects did not performed differently from typical readers across graph types; and (8) There was a three-way interaction between group, graph type and question type for comprehension accuracy. For the line and bar graphs, the difference between dyslexics and typical readers was larger for comparison questions than for point locating questions. This pattern was not observed for the horizontal bar graphs. In addition, there was a three-way interaction between graph type, graphic display and question type for the viewing times. For both line and bar graphs, the difference between single and double graphic displays was larger for graphs associated with comparison questions than graphs associated with point locating questions. This pattern was not observed for horizontal bar graphs.

Results for the question 3 are as follows: (1) The eye fixation data in the linguistic text regions (i.e., location of questions and answers) revealed that students with dyslexia spent significantly longer times reading text than typical readers; and (2) The eye fixation data in the graphic pattern regions revealed that when participants initially looked at the graph (first pass), there was no difference between the two groups. However, the entire time spent in the pattern area was longer for the students with dyslexia than for the typical readers.

Results for the question 4 are as follows. (1) Dyslexics' performance on graph interpretation correlated significantly with several working memory variables, while typical readers' performance correlated significantly with several executive function skills; and (2) On vocabulary and other cognitive variables (i.e., working memory and executive functions), dyslexics' scores were significantly lower than typical readers' scores.

CHAPTER 5
DISCUSSION

This study was designed to investigate group differences between dyslexic and non-dyslexic young adults on their interpretation of graphs and to determine if the groups differed when the latent variable of subjects' familiarity and experience with graphs was controlled and when graph complexity and question complexity were assessed. The specific aims of this study were 1) to compare comprehension accuracy of the two groups at different levels of complexity for graphs and questions; 2) to compare the eye gaze patterns of the two groups at different levels of complexity for graph and question; 3) to compare the two groups on the amount of time that they spent looking at specific subregions of graphs (i.e., pattern, x-axis, y-axis, legend, question, answer); and 4) to explore relationships between the participants' accuracy and speed of graph interpretation, receptive vocabulary, and cognitive abilities for working memory, attention, and inhibition.

Fifteen college students with dyslexia and 20 control peers were asked to look at each graph presented with a question on a computer screen and answer written questions while their eye movements were being tracked. Three types of graphs (i.e., line, bar, and horizontal bar graphs), two types of graphic displays (i.e., single and double graphic displays), and two types of questions (i.e., point locating and comparison) were used to measure the effect of graph type and question type on the subjects' graph interpretation.

Group Comparisons on Graph Interpretation Accuracy

The results revealed differences between the two groups on comprehension accuracy, even though the differences were numerically small. Students with dyslexia performed significantly more poorly than typical readers on the graph interpretation tasks. This finding is consistent with previous research on the graph comprehension skills of individuals with learning disabilities.

Parmar and Singer (2005) reported that elementary school children with learning disabilities had more difficulty interpreting line graphs than their peers without learning disabilities, and Curcio (1982) reported that reading achievement is a unique predictor of graph comprehension in fourth and seventh graders.

Across the two groups, comprehension accuracy was significantly lower on the horizontal graphs than on the line or the bar graphs. While the three graph types consists of an x-axis and a y-axis, the horizontal bar graph requires a different visual orientation because the axes are reversed. Shah and Hoeffner (2002) noted that people typically assume the x-axis to be the independent variable and the y-axis to be the dependent variable. The horizontal bar graph violates this expectation and may account for the participants' lower graph interpretation scores. This finding, showing an association between task difficulty and specific graph features appears to support the *perceptual feature view,* previously discussed, in which different graphic features activate different mental representations (Lohse, 1993), as opposed to the *invariant structure view,* that posits all graphs are mentally represented in similar ways.

In addition to differences found across graph types, in the current study, differences were also found when a graph was made more complex by including additional data. For example, participants were less accurate in interpreting graphs with double graphic displays (e.g., double line graph) than with single graphic displays (e.g., single line graphs). This finding is consistent with the result of several previous studies of graphic displays (e.g., Carpenter & Shah, 1998; Shah & Carpenter, 1995; Shah & Hoeffner, 2002).

The question type variable has been the most widely studied in the context of graph comprehension (e.g., Bright, Friel, & Lajoie, 1998; Carswell, 1992; Curcio, 1982; Curcio, 1987; Pereira-Mendoza & Mellor, 1991; Wainer, 1992). In their review of the research on the effects of graph comprehension, Friel, Curcio, and Bright (2001) characterized the point locating questions as ‘read the data’ questions and comparison questions as ‘read between the data’ questions. They concluded that ‘read between the data’ questions were more challenging to graph viewers.

In the current study, interactions were found between groups and graph variables. There was a significant difference between the students with dyslexia and typical readers for the comparison questions with dyslexic readers scoring less accurately. However, there was no significant difference between the two groups for point locating questions although the accuracy scores for the dyslexic group were numerically lower. This finding suggests that graph comprehension difficulty in dyslexics deteriorates as the complexity of the stimulus increases. The effect of stimulus complexity has been consistently reported in children and adults with dyslexia (Fawcett & Nicolson, 2007; Park, 2011). Furthermore, significant interactions between graph type (i.e., line, bar, horizontal bar graphs) and graphic display (i.e., single and double graphic displays) was found. This interaction suggests that when tasks involve both complex graphic stimuli and complex questions, individuals who have processing deficits, such as dyslexia, may be faced with much greater challenges than their peers who do not have a learning disability.

Group Comparison on Graph Viewing Times

Overall, the eye tracking data were consistent with the comprehension accuracy data. Students with dyslexia needed significantly longer time than typical readers in completing graphic tasks. All participants took longer to interpret graphs associated with double patterns than graphs with single patterns and graphs presented with comparison questions than graphs with point locating questions.

In addition, there were significant interactions between group and question type, group and graphic display, and question type and graphic display. Dyslexic participants spent significantly longer looking at graphs presented with comparison questions than graphs associated with point locating questions. Also, dyslexics spent longer times looking at graphs with double graphic patterns than those with single graphic patterns. Again, these findings underscores that level of complexity has a greater effect on the response times of individuals who have learning disabilities than on typical learners. The interaction between question type and graphic display shows that when the complex stimuli were associated with complex questions, they were more likely to result in less accurate and slower responses.

In examining the eye fixation times on graph comprehension tasks, visual displays were segmented into six areas of interest (i.e., x-axis, y-axis, pattern, legend, question, answer). The eye tracking data showed that the students with dyslexia fixated for significantly longer periods of time in the linguistic text regions (i.e., where questions and answers were located). The group difference was found both in the first pass time and the total viewing time. This finding suggests that the greatest time differences between the groups in graph interpretation occurred while processing the text area regions. Among the four graphic regions (x-axis, y-axis, pattern, legend), dyslexics spent longer time than typical readers in the pattern region only. This longer period of viewing time was only found in the total reading time, not on the first pass. The students with dyslexia needed a longer time to process the pattern after the initial viewing of that region.

Impaired visual processing in dyslexia, in some form or another, has been suggested as a potential cause of dyslexia. Dyslexia was first described in the literature in the 18^{th} century by Dr. Samuel Orton and referred to as *wordblindness* or *strephosymbolia* (Orton, 1928, 1943). Since then, many theories regarding the biological underpinnings of dyslexia have been posited. For example, some researchers argue that there is a high correlation between visual analytical skills and reading achievement (Garzia, 2000; Grisham, Powers, & Riles, 2007; Stein, 2008) and suggest three subtypes of dyslexia exist, the phonological processing deficit type, the visual processing deficit type, and the phonological and visual processing deficit type (Stein, Talcott, & Walsh, 2000). Others, however, argue that visual deficits are found only in small group of individuals who have dyslexia (Johannes, Kussmaul, Münte, & Mangun, 1996; Victor, Conte, Burton, & Nass, 1993) and conclude that visual processing deficits are likely to be symptoms of linguistic deficiencies, rather than a cause of this disability (American Academy of Pediatrics, 2010). This study revealed that most of the between group differences were found in the viewing times associated with the text areas.

Findings from Language and Cognition Measures

The dyslexic subjects' performance on graph interpretation was more strongly related to their working memory capacity, while typical readers' performance was more strongly related to their executive function skills. It is possible that the graphic stimuli (including graphics and text) may have become overlearned (three types of question and graph were repeated 48 times, respectively) for typical readers to the extent that they had fewer demands on verbal working memory. In contrast, the dyslexics may not have had this advantage and were required to rely on working memory to a greater extent.

Dyslexics' text viewing times correlated with all verbal working memory measures (i.e., digit forward, digit backward, and digit ordering subtests). Previous studies have consistently reported that dyslexics' impaired reading correlates with reduced verbal short-term and working memory span. Griffiths & Snowling (2002) found that verbal memory span was the unique predictor of reading in 9–15-year-old dyslexic children. Berninger and colleagues (2006) and Smith-Spark and Fisk (2007) showed that verbal memory difficulties in dyslexia extend into adulthood and affect performance in reading and academic achievement. Vocabulary was not related to either dyslexics' or typical readers' performance on graph interpretation because words in this study were carefully controlled in terms of difficulty. The close association between verbal working memory and text viewing time in dyslexic readers suggests that, perhaps, it is not vocabulary per se, but the cognitive resources to actively maintain or store the meanings of the words in questions may be impaired in dyslexics.

Block recall subtest correlated significantly with graphic viewing times in both dyslexic and typical reader groups. Block recall measures the ability to analyze and synthesize the composite parts of visual patterns and to reproduce the pattern from tester's demonstration (Meyler & Breznitz, 1998). Visual dimensions (i.e., shape, color, length, etc.) in a graph should be analyzed and synthesized to comprehend the graph and to answer to the related questions. Thus, significant correlation between graphic viewing times and the block recall test scores is predictable. In addition, the block recall correlated with text viewing time in typical readers, but not in dyslexic readers. It is currently not universally agreed that visuo-spatial memory contributes to verbal information processing. Hulme, Snowling, Caravolas, and Carroll (2005) found that visual memory did not play a significant role in the reading and spelling of 153 elementary school children. Bayliss, Jarrold, and Gunn (2003) explored the relationship between visual working memory and reading and math performance in typical adults. The investigators reported non-significant correlation between the visual memory variable and reading and math ability. In contrast, other researchers have reported that visual memory is associated with reading as strongly as verbal memory. In their longitudinal study of pre-reading children, Meyler and Breznitz (1998) found that the influence of visual memory was stronger and more consistent than influence of verbal memory while both visual and verbal memory played an important role in the acquisition of reading. Visual memory predicted not only reading accuracy but also reading speed of second-grade children. Based on this result, they suggested that visual memory may be more critical for reading speed, while verbal memory may be important for later reading accuracy. In the current study, the correlation between block recall test scores and text viewing time, not comprehension accuracy for the typical readers may support their argument.

Among all execution function test scores, Stroop word task correlated mostly highly with the graph viewing time. The Stroop task is a popular measurement of inhibition (or resistance to interference) and suppression of automatic responses in order to process less automatic responses (Brocki & Bohlin, 2004). A diminished capacity for inhibition has been viewed as a key executive function deficit affecting reading skill (Smith-Spark & Fisk, 2007). In the present study, Stoop color-word scores correlated with text viewing time in both typical readers and dyslexic readers. The next largest correlation coefficient was found in the relationship between graphic viewing time and Digit Symbol Substitution subtest. This task entails the ability to match a familiar stimulus (i.e., digit) with a novel stimulus (i.e., an abstract symbol that may look similar) in a timed condition (Venkatraman, et al., 2011). Digit Symbol Substitution has some features in common with graph interpretation in that graphic task used involved making rapid connections between symbols and conceptual referents. Also, Digit symbol substitution was one of the only two executive function skills significantly correlated with graph viewing times in dyslexic readers.

Even though it is not directly related to the research question, it is worth noting that dyslexic readers had significantly lower scores than typical readers on the receptive vocabulary measure and on all other measures of cognition. In a previous study by Wiseheart, Altmann, Park and Lombardino (2009), young adults with and without dyslexia did not differ in their scores on the Shipley vocabulary test. The average vocabulary scores of dyslexic readers and typical readers in their experiment were 30.22 and 31.80, respectively, while in the current study, the scores were 27.13 and 31.00, respectively. Thus, the scores of typical readers were similar between the two studies, but the scores for dyslexic readers in this study were lower than those in Wiseheart et al. (2009). It appears that dyslexic subjects in the current study had overall more severe learning disabilities than the dyslexic subjects in the Wiseheart et al. (2009). Most of the dyslexic participants in this study were referred by the University of Florida Disability Resource Center because they were at risk of failure in their classes. Given that the performance of the dyslexic group in this study was lower on the other cognitive measures (e.g., working memory scores) than in the Wiseheart et al. (2009) study, it may be that the present study included more severely impaired dyslexics. Another possible reason for the inconsistency between the current data and the Wiseheart et al. (2009) data is the dispersion of scores in the dyslexic readers. The difference of scores (i.e., subtracting the smallest score from the largest one) for typical readers in the current study was 16 (the range was 37 and 21) while the difference for dyslexic readers was 23 (the range was 37 and 14). Three students in the dyslexic group had scores lower than 19 (total score was 40), where as none in typical group had such low scores.

On all verbal working memory cognitive measures, the dyslexic group in this study performed more poorly and slowly than their peers without dyslexia, supporting a considerable body of evidence of impaired verbal working memory in individuals who have dyslexia. (for a review see Snowling, 2000). Menghini, Finzi, Carlesimo, & Vicari (2011) summarized three hypotheses in an attempt to account for the association between poor verbal working memory and dyslexia: (1) an impairment of subvocal rehearsal mechanisms might be responsible for dyslexia (Baddeley, 2003); (2) A reduced speech rate may be associated with both impaired subvocal rehearsal system and reading deficits (McDougall, Hulme, Ellis, & Monk, 1994); and

(3) an impairment of phonological store, rather than subvocal rehearsal lies at the root of these verbal working memory deficits (Kibby, Marks, Morgan, & Long, 2004).

Evidence is inconclusive regarding the involvement of visual working memory in dyslexia. Indeed, some studies have reported that visual working memory, in contrast to verbal working memory, is intact in dyslexic individuals. Jeffries and Everatt (2004) noted that the difference between dyslexic children and typical readers was found on verbal working memory measures, but not on visual working memory measures (using visual-spatial sketch tasks). Similarly, Kibby et al. (2004) reported that children with dyslexia have impaired phonological loop functions, but intact visual-spatial sketch pad functions. In contrast, other researchers have reported impaired visual working memory in dyslexics. Smith-Spark and Fisk (2007) compared performance of verbal and visual working memory measures in two groups of adults, dyslexics and age and IQ-matched typical readers. They found that dyslexics were impaired on both verbal and visual tasks of simple and complex span. Based on these findings, some researchers suggest that the deficits found in individuals with dyslexia are domain-general rather than domain-specific (Cohen-Mimran & Sapir, 2007). Based on processing speed data using linguistic and non-linguistic stimuli presented in both the visual and motor modalities, Park (2011) found that visual working memory, as well as verbal working memory, is impaired in dyslexia, but the deficits are less severe for visual working memory than for verbal working memory.

The difference between dyslexic and typical readers was also apparent in the executive function tasks. Indeed, the effect sizes (i.e., a measure of the magnitude of the observed effect; Field, 2009) for the executive functions (partial η_2 =.45) was larger than for verbal working memory (partial η_2 =.27) and visual working memory (partial η_2 =.18). Executive function refers to cognitive abilities such as planning, sequencing, persistence, inhibition, and flexibility of action, and is linked to the prefrontal cortex of the brain (Brocki & Bohlin, 2004). Smith-Park and Fisk (2007) found that young adults with dyslexia showed significant deficits in executive function compared to typical readers, after controlling for working memory performance. They argued that the central executive impairments demonstrated by dyslexics are a domain -general processing problem, independent of verbal or visual working memory and that executive functions are the major cognitive factors associated with dyslexics' reading impairments. Their finding supports Nicolson and Fawcett's (1990) *Dyslexic Automatization Deficit* (DAD) hypothesis. The DAD hypothesis posits that dyslexics have impaired automatization abilities overall, which, in turn, place a burden on their attentional capacity for the task they are involved. Overall, Fawcett and Nicolson (1990; 2001) and Smith-Spark and Fisk (2007; 2003) argued that dyslexics' automatization impairments are revealed in four types of skills: (1) complex skills requiring fluency; (2) time-dependent skills; (3) multi-modality skills; (4) vigilance tasks associated with concentration over time.

Theoretical Implications

There are several potentially important theoretical implications associated with the findings from this study. Due to the large number of analyses conducted, these implications are presented below: (1) Graph comprehension is influenced by various variables including the graph viewer's abilities, the graphical properties, and the specific requirements of the given task. In addition, these variables are closely related to each other and the influence of one variable is dependent upon the other ones. Therefore, it is important to consider the close interaction among perceptual processes (e.g., interpreting the patterns/lines), conceptual processing (e.g., interpreting questions), and the graph viewer's ability (e.g., cognitive abilities or graph familiarity) when examining graph comprehension; (2) As in many other studies, the present study showed that dyslexic's deficits are not restricted to reading performance. That is, the dyslexics needed longer time to process not only text, but also pictures. However, it is worth noting that for the verbal stimuli (question and text), the difference between dyslexics and typical readers was larger than for the non-verbal stimuli; (3) The dyslexic adult's poorer graph comprehension was most apparent on the complex tasks (e.g., double horizontal bar graphs). This finding supports other data showing that dyslexics are more challenged when the stimulus is complex (Meyler & Breznitz, 2005; Nicolson & Fawcett, 1994; Stein & McAnally, 1995); (4) Dyslexic's graph interpretation correlated closely with several working memory measures including verbal and visual, while typical readers' graph interpretation correlated closely with several executive function skills; and (5) The present study supports that dyslexia is characterized by a range of cognitive deficits that are not limited to reading skills. Young adults with dyslexia performed significantly poorer than their peers without dyslexia not only on verbal working memory, but also on visual working memory and executive function tasks.

Clinical Implications

Findings from this study are very relevant to the education of students with dyslexia. Graphing is a fundamental part of the curriculum (Kramarski, 2004; National Council of Teachers of Mathematics, 2000) and the present study revealed that young adults with dyslexia performed significantly less accurately and more slowly in interpreting graphs than typical readers, even when the stimuli were elementary level graphics.

There is a need for testing nonverbal skills in dyslexics. In a clinic setting, the evaluation of dyslexia appears to focus on language skills. However, this study is consistent with previous studies showing that dyslexics' impairments can influence their processing of other stimuli such as graphs that include verbal and visual variables. To my knowledge, there is currently no standardized graphic skill measurement. Some researchers and educators have used the Test of Graphing in Science (TOGS; McKenzie & Padilla, 1986). This 26-item multiple-choice test is developed to measure graphing skill. The developers indicated that the test has content validity by showing that a panel of reviewers agreed over 94% of the time on assignment of items to objectives and 98% on the scoring of items. The test is used to measure elementary level graph interpretation skills targeting upper elementary school or lower middle school students. Another test, the Graphing Interpretation Skill Test (GIST; Svec, 1995) contains eleven multiple-choice items. This task was based on the TOGS by McKenzie & Padilla (1986) and was developed to measure high-school or college students' graphic interpretation skills.

The results of this study also support the development of intervention programs that focus on visual information interpretation skills for dyslexics. This study demonstrated that longer time does not guarantee better performance for dyslexics. Even when the dyslexic students spent significantly longer time to solve the graphic questions, their accuracy scores were still significantly lower than their peers. The most common accommodation for students with learning disabilities is the provision of extra time to complete assignments, quizzes, and examinations. Data from this study indicate that, while additional time may be a necessary accommodation, it is not a sufficient accommodation. Students with dyslexia could profit from more explicit and intensive intervention in the area of graph interpretation.

Parmar & Signer (2005) provided the following recommendation for teaching graphics to students: (1) Students need to explicitly learn information on the framework of the graph and its referents, such as how to label the axes, what scale is used for measure, and what type of information is presented; (2) Educators need to emphasize scale markings and making interpolations and extrapolations; (3) Students need to experience higher levels of thinking in interpreting graphic data, such as interpreting data from two or more variables concurrently or comprehending trends; (4) Students should be encouraged to use the mathematical terms related to the description of relationships, such as “the same as”, or “twice as much as.”; and (5) Educators need to encourage students to write stories based on graphs or construct graphs based on stories. In addition, Keller (2009) recommended that educators consider the importance of automaticity on graphing tasks as well as accuracy. Automaticity should free up the graph viewer’s cognitive resources to be used for sophisticated graph interpretation. Keller (2009) also stated that students need to be encouraged to analyze graphed data based on their background knowledge or real life experiences, instead of interpreting data without using prior knowledge as a point of reference.

Limitations and Future Directions

This study demonstrated that young adult dyslexic’s graph comprehension is less accurate and slower than typical readers by analyzing participants’ response accuracy and eye gaze data. Future research on graph comprehension should extend our knowledge base.

Firstly, even though this study showed differences between the two groups, the mean differences (especially on comprehension accuracy) were numerically small. The simplicity of the stimuli may played a role in this finding. The stimuli were elementary grade-level graphs and may have been too easy for college students. The processing of simple graphs may not be comparable to the processing of more complex graphs (Ratwani & Trapton, 2008; Shah & Freedman, 2009). In meaningful contexts such as in social science, graphs can present relatively complex data, requiring processing of information that is not explicitly presented (Shah, et al., 1999; Tricket & Trafton, 2006) and graphs may be more helpful when the data is more complex. Therefore, future research should attempt to use more age-appropriate stimuli.

Secondly, while this study revealed that dyslexic’s performance on graph tasks was significantly poorer than typical readers, their comprehension of graphs might still be better than their comprehension of passage reading. To investigate this issue, the same information in this study could be provided in the form of text. A future study should be conducted to compare response accuracy and/or response time when information is presented in two formats, text and graphs. It is widely accepted that visual displays enhance the comprehension of data; however, recently, advantage of textual over graphical representation of information has been reported (Van Der Meulen, et al., 2010). Thus, such research would further our understanding of graph processing.

Thirdly, this study allowed participants to spend an unlimited amount of time to process the graphs. Future studies should adopt the system-paced time method, in which the length of each scene is controlled by computer. This methodology may reveal even clearer differences in the performance between dyslexics and typical readers. The comparison of system-controlled and self-controlled data processing has recently captured the attention of researchers, especially those involved in multimedia learning research (Schmidt-Weigand, et al., 2010).

Finally, extending this research to include graph *production* would contribute to the understanding of the graph processing of dyslexics as well as typical readers. Leinhardt, Zaslavsky, & Stein (1990) pointed out that graph construction is different from graph interpretation because interpretation comes from a given piece of data, while the construction requires the generation of new parts. It is likely that dyslexics have more difficulty producing graphs than interpreting them because construction relies on higher cognitive processing (Kramarski, 2004).

APPENDIX A
RECRUITMENT FLYER

Volunteers Needed

To participate in a graph reading study

"Visuals in the Mind's Eye: Investigating graph comprehension of students"

Researchers: Linda J. Lombardino, PhD., Sunjung Kim, MA

UF-IRB: ____________ (For use through_______)

Estimated duration of experiment: 3 hours

In this study, you will see graphs on a computer screen and be asked to identify certain features to answer questions they've just read while the movement of your eyes is monitored and their position recorded. The experiment should take three hours or less.

To participate in this study, you must be a native speaker of English, age 18-35, with normal or corrected vision.

Two groups of subjects needed:

Group 1 - Students who have no history of difficulty with reading or spelling

Group 2 - Students who have had reading or severe spelling difficulties since elementary school. These students may have no diagnosis or may have a diagnosis of a learning disability, reading disability, processing disability or dyslexia.

- **If you are not sure if you have a reading disability but suspect that you might, we will do a screening to find out!**
- **All participants with reading disability will be given a three-page brief report of their test findings if they choose to be informed of their standardized test scores for documentation of their learning disability.**
- **For applicable courses, participants will be compensated in the form of 2 hours of research cred it.**

Reference "Experiment" in the subject line of your email to set up an appointment with:

Sunjung Kim (kimsj0591@ufl.edu)

APPENDIX B
INFORMED CONSENT LETTER FOR PARTICIPANTS

Visuals in the Mind's Eye: Investigating graph comprehension in students

Please read this consent document carefully before you decide to participate in this study.

Purpose of the research project
The purpose of this study is to examine how people comprehend graphs to answer comprehension questions.

What you will be asked to do in the study

If you agree to participate, then you will see graphs on a computer screen and be asked to identify certain features to answer questions they've just read while the movement of your eyes is monitored and their position recorded. The experiment should take three hours or less.

We will provide you with short breaks between tasks, and you can ask for a longer break at any time. All testing will be carried out by the principal investigator, Dr. Lombardino, or trained research assistants in her lab.

Time required
The study involves a one-time visit that lasts about 3 hour.

Risks and Benefits

There are no known risks involved in this experiment, apart from those involved in everyday life. You will receive one half-hour of course credit for each 30 minutes of participation (rounded up).

There will be no direct benefit to you for participating in this experiment (apart from the educational experience), although the experiment should help the scientific community and the public at large to gain an increased understanding of the human ability to use language.

Compensation

There will be a non-research alternative for extra credit, if you choose the extra credit for compensation. Instructors preserve rights of determining the options for the course credit. If instructors want examiners to decide the alternative, you can read a short research article related to graph comprehension and write a 1.5-2 page synopsis of it and receive the same amount of course credit. You can choose any articles related to graph comprehension research. The extra credit for participation is limited to no greater than the equivalent of 2% of the student's overall grade in the course.

Confidentiality

Your identity will be kept confidential to the extent provided by law. Your information and recordings will be assigned a code number for identification. The list connecting your name to this number will be kept in a locked file in the principal investigator's lab. When the study is completed and the data have been analyzed, the list will be destroyed. Your name will not be used in any report. Test results and recordings will be archived for research purposes, but your name will in no way be associated with these results.

Voluntary participation
Your participation in this study is completely voluntary. There is no penalty for not participating.

If you choose not to participate, there are research and non-research alternative options for this extra credit that will take relatively the same amount of time and effort as this opportunity.

Right to withdraw from the study
You have the right to withdraw from the study at any time without penalty.

Whom to contact if you have questions about the study
Linda J. Lombardino, Ph.D.
Department of School of Special Education, School Psychology, and Early Childhood Studies, University of Florida
P.O. Box 117050; Gainesville, FL 32610
Office: (352) 273-4279; Email: **llombard@ufl.edu**

Whom to contact about your rights as a research participant.
UFIRB Office, P.O. box 112250, University of Florida, Gainesville, FL32611-2250
352-392-0433.

Agreement
I have read the procedure described above. I voluntarily agree to participate in the procedure and have received a copy of this description.

Participant: ____ **Date:**__________

Principal Investigator: ____________________________________ **Date:**__________

Experimenter: ____ **Date:**__________

KEEP THIS FORM TO CLAIM YOUR COURSE CREDIT !
Check your syllabus for details

APPENDIX C
QUESTIONAIRE FORM

Subject # ________________________________Study__________________________Score__________
Visit ____________________________________Group _________________________Tester__________

1. Age _____
2. Gender _____ Female _____ Male
3. What is/are your majors (s)? _____
4. Have you taken any math or statistics classes during your undergraduate and/or graduate studies? How many have you taken?

   Math _____ yes _____ no how many _____

   Statistics _____ yes _____ no how many _____

Below are several statements concerning your experience using graphs. Please chose a number from 1-7 and write it next to each statement to indicate the frequency with which you perform each task.

1	2	3	4	5	6	7
Never						Very often

1. ____ I need to interpret graphs as part of my job or field of study.
2. _____ I read graphs in the popular press (e.g., magazines, newspapers).
3. _____ I use a software package to produce graphs.
4. _____ I notice errors or misrepresentations in graphs presented in academic journals or the popular press (e.g., magazines, newspapers).
5. _____ When I look at a graph, I try to understand the main point the creator of the graph was trying to make.
6. _____ When I look at a graph, I try to identify the overall patterns or trends represented.
7. _____ When I look at a graph, I think about the likely reasons for the pattern(s) of data presented.

Please chose a number from 1-7 and write it next to each statement describing your typical reaction to graphs.

1	2	3	4	5	6	7
Never						Very often

8. ____ When I encounter a graph in a text, newspaper, or magazine, I tend to ignore it (skip it completely).

9. _____ When encountering graphs, I usually “skim” the graph for an overall idea of what it represents, but I do not study it in detail.

10. _____ I find graphs useful for remembering information.

11. _____ I would prefer seeing a table of numbers rather than seeing a graph of the numbers.

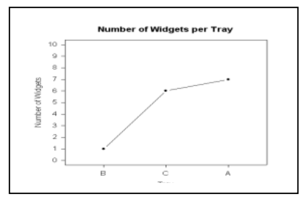
12. _____ Graphs are generally a waste of space.

13. _____ Overall, on a scale of 1 to 6, how useful do you find graphs?

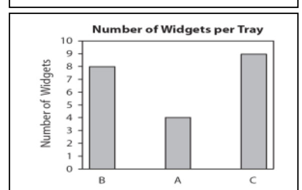
Below are several questions concerning your graph-reading ability. Please chose a number from 1-7 and write it next to each statement to indicate the extent to which you agree or disagree with each statement.

1	2	3	4	5	6	7
Strongly disa gree						Strong agree

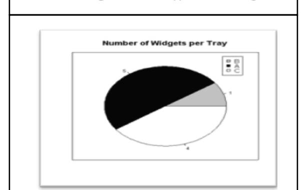
14. ____ I am familiar with reading line graphs.



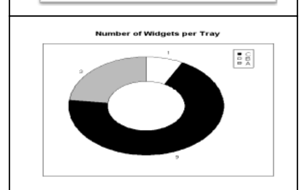
15. _____ I am familiar with reading bar graphs.



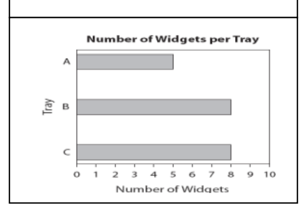
16. _____ I am familiar with reading pie charts.



17. _____ I am familiar with reading donut graphs.



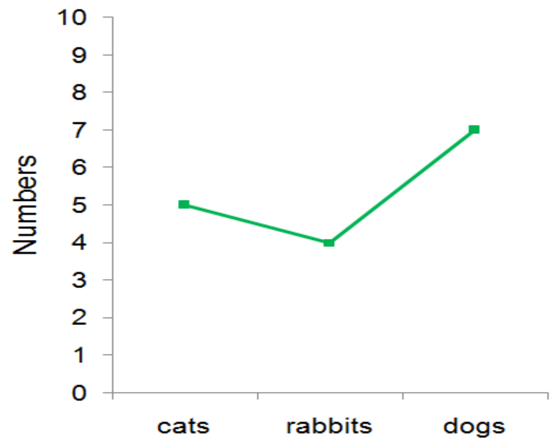
18. _____ I am familiar with reading horizontal bar graphs



19. _____ Overall, on a scale of 1 to 7, how would you rate your ability to read graphs?

APPENDIX D

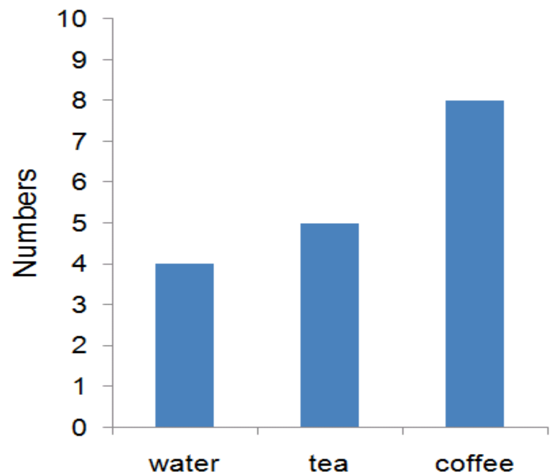
SAMPLE OF SINGLE GRAPHIC DISPLAY GRAPH AND QUESTION

<table>
<tr>
<td>


</td>
<td>
Jackie loves her animals. How many cats does she have?

4 5

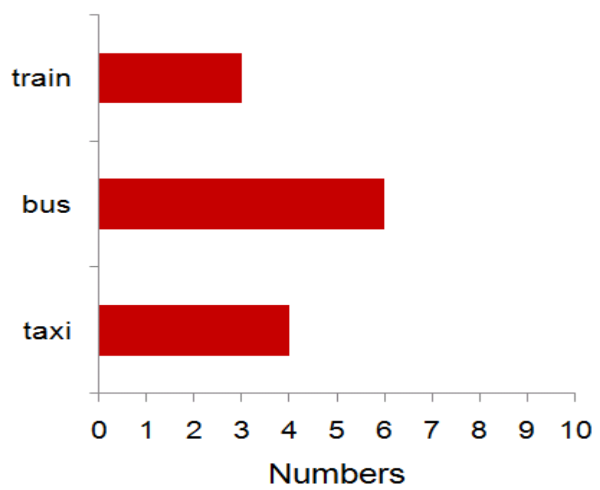
Jackie loves his animals. Does she have more rabbits than dogs?

No Yes
</td>
</tr>
<tr>
<td>


</td>
<td>
Harry drinks a lot of things. How many cups of teas did he drink?

5 8

Harry drinks a lot of things. Did he drink more cups of water than cups of coffee?

No Yes
</td>
</tr>
<tr>
<td>


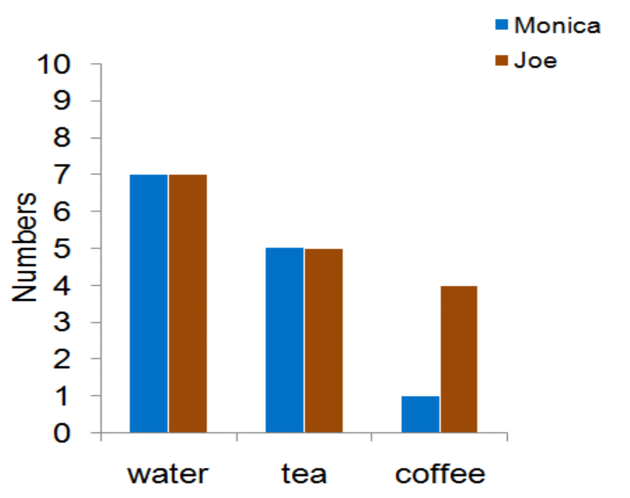
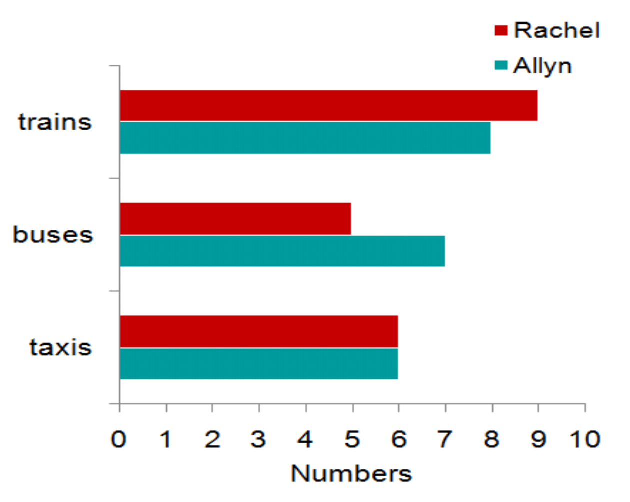
</td>
<td>
Alissa has to ride to work this week. How many train rides did she take?

6 3

Alissa has to ride to work this week. Did she take more bus rides than taxi rides?

No Yes
</td>
</tr>
</table>

APPENDIX E
SAMPLE OF DOUBLE GRAPHIC DISPLAY GRAPH AND QUESTION

	Stella loves her animals. How many dogs does she have? 9 7 Stella loves her animals. Does she have more cats than rabbits? No Yes
	Joe drinks a lot of things. How many cups of water did he drink? 5 7 Joe drinks a lot of things. Did he drink more cups of tea than cups of coffee? No Yes
	Rachel has to ride to work this week. How many taxi rides did she take? 9 6 Rachel has to ride to work this week. Did she take more bus rides than train rides? No Yes

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BIOGRAPHICAL SKETCH

Sunjung Kim graduated from the Ewha Woman's university in 2003 in psychology. In 2005, she received her Master of Arts degree in speech-language pathology from the same school. Her master's thesis, *Development of Phonological Processing Abilities of Children in the age of 3 to 6*, was chaired by Dr. Youngtae Kim. Sunjung has worked as a speech-language pathologist since graduation. This clinic experience provided a foundation for literacy difficulties of dyslexia grounding this research project. In 2007, she came to the University of Florida to pursue doctoral studies in the department of Speech, Language, and Hearing Sciences and have an interdisciplinary specialization through educational psychology in the area of reading comprehension. She received her Ph.D. from the University of Florida in the summer of 2012.