UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

DISCOVERING ACCESSIBLE DATA VISUALIZATIONS FOR PEOPLE WITH ADHD

A THESIS

SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
Degree of

MASTER OF SCIENCE

By

Tien Giang Tran
Norman, Oklahoma
2024

DISCOVERING ACCESSIBLE DATA VISUALIZATIONS FOR PEOPLE WITH ADHD

A THESIS APPROVED FOR THE
GALLOGLY COLLEGE OF ENGINEERING

BY THE COMMITTEE CONSISTING OF

Dr. Ji Hwan Park, Chair
Dr. Charles D. Nicholson
Dr. Lauren Ethridge

ACKNOWLEDGMENTS

I thank Dr. Charles Nicholson, Dr. Lauren Ethridge, Dr. Ami Bax, Dr. Talayeh Razzaghi, and Thomas Salas for their consultation and guidance.

I acknowledge and thank Dr. Hae-Na Lee and Dr. Ji Hwan Park for their help in writing this Thesis. I, Tien Tran, planned and conducted the survey, conducted all cleaning and analysis of the data, created all figures shown in the work, and contributed to most of the writing. Dr. Lee and Dr. Park helped to write and edit this work. Thank you for your kindness, dedication, and time. The results of this Thesis will be published under the following citation:

Tien Tran, Hae-Na Lee, and Ji Hwan Park. 2024. Discovering Accessible Data Visualizations for People with ADHD. In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI '24), May 11– 16, 2024, Honolulu, HI, USA. ACM, New York, NY, USA, 19 pages. https: //doi.org/10.1145/3613904.3642112

LAND ACKNOWLEDGMENT

Long before the University of Oklahoma was established, the land on which the University now resides was the traditional home of the “Hasinais” Caddo Nation and “Kirikirʔi:s” Wichita & Affiliated Tribes.

We acknowledge this territory once also served as a hunting ground, trade exchange point, and migration route for the Apache, Comanche, Kiowa and Osage nations.

Today, 39 tribal nations dwell in the state of Oklahoma as a result of settler and colonial policies that were designed to assimilate Native people.

The University of Oklahoma recognizes the historical connection our university has with its Indigenous community. We acknowledge, honor and respect the diverse Indigenous peoples connected to this land. We fully recognize, support and advocate for the sovereign rights of all of Oklahoma’s 39 tribal nations. This acknowledgement is aligned with our university’s core value of creating a diverse and inclusive community. It is an institutional responsibility to recognize and acknowledge the people, culture and history that make up our entire OU Community.

The above land acknowledgement statement was created by the OU Land Acknowledgement Working Group in August of 2020.

DEDICATION

Dedicated to my parents, Steve and Phuong; to my brothers, Minh, Benjamin, and Tommy; to my family, and to all of my friends and loved ones who have ADHD. I may be the captain of this ship, but you are the stars which guide me.

TABLE OF CONTENTS

ABSTRACT

There have been many studies on understanding effective data visualizations regarding general users. However, we have a limited understanding on how people with ADHD comprehend data visualizations and how it might differ from the general users. To understand accessible data visualization for people with ADHD, we conducted a crowd-sourced survey involving 70 participants with ADHD and 77 participants without ADHD. Specifically, we tested the chart components of color, text amount, and use of visual embellishments/pictographs, finding that some of these components and ADHD affected participants' response times and accuracy. We outlined the neurological traits of ADHD and discussed specific findings on accessible data visualizations for people with ADHD. For example, we found that various chart embellishment types affected accuracy and response times for those with ADHD differently depending on the types of questions asked. Based on these results, we suggested visual design recommendations to make more accessible data visualizations for people with ADHD.

Chapter 1

Introduction

A tremendous amount of data is generated every day, and the use of this big data continues to become more prevalent. Hence, the importance of data literacy rises. The ability to understand data is required now more important than ever to make crucial decisions, including financial, educational, and medical decisions. Data visualizations are often very helpful in making these vast quantities of data more comprehensible and digestible, and there has been a lot of research on the effects of data visualizations on general populations. These works have studied the best uses of color [63, 69, 71, 78, 87], the best amount of text [36, 41, 47, 48, 77], and the effects of different chart types [11, 12, 15].

As the reliance on digital visualizations has increased, data scientists and the visualization community have become increasingly aware of the divide between those who can and cannot access important data via existing visualization methods. For example, the rise in technological advances has contributed to a widening gap in accessibility as people with visual disabilities are unable to interpret increasingly complex data visualizations that new techniques provide [19, 27].

The question on how to create accessible data visualizations has been the topic of many recent studies. Some researchers explored accessible visualizations for people who are blind or vision impaired [43], people with intellectual and developmental disabilities [84, 85], and people with photosensitive epilepsy [75]. However, little research has been conducted on whether visualizations can be adapted to be accessible for individuals with attention-deficit/hyperactivity disorder (ADHD). ADHD is a neurological disorder that manifests as "impairing levels of inattention, disorganization, and/or hyperactivity-impulsivity". For many individuals, ADHD may limit effective communication, social participation, or academic achievement [6, 33]. Because of these traits, the disorder is often linked to inhibiting a person's ability to digest or analyze information. This is a concern as data-driven decisions become more frequent in people's everyday lives.

Data visualization guidelines and perception research that apply to a general audience may not be inclusive for people with ADHD, which is a neurodevelopmental disorder. For example, in the context of color, adults with ADHD showed deficits in responding to blue stimuli [44]. ADHD has also been shown to hinder reading ability, so those with ADHD might be affected by the amount of text used in data visualizations [21, 60, 61].

The amount of research on accessible data visualizations for ADHD is insufficient considering the prevalence of ADHD today. Rates of diagnosis for ADHD among college students are 7.11% in Canada and are ranging from 2% to 8% in the United States [53]. Also, approximately 2.5% of adults around the world were estimated to have ADHD [73]. Thus, there is a need to further study the effects of ADHD in the fields of computer science and data communication to understand how people with ADHD interpret data visualizations and to provide accessible forms if there are any challenges confronted by those with ADHD.

In this thesis, existing research related to ADHD and accessible data visualizations were surveyed. This work outlined ways in which the body of work for accessible visualizations can be expanded. To do so, a crowd-sourced survey was conducted of 147 participants to test the effect of different chart components – color (hue), text amount, and embellishments/icons – on response time and accuracy for people with and without ADHD. It was found that changing these chart components did not significantly affect the responses of those with ADHD compared to the control group. The use of minimal text in graphs correlated with higher performances in both groups. In addition, the responses of those with ADHD to charts using visual embellishments and pictographs were dependent on the task. Based on the findings of this study, it was proposed preliminary guidelines on how to make data visualizations more accessible and effective for those with ADHD. It was also found evidence that the preferences and personal interests of the viewer did not correlate with performances, but the activation of hyperfocus through enjoyment or stress might need to be considered when designing equitable visualizations. The main contributions of this thesis are:

- We conducted an online crowd-sourced study that included both people with ADHD and people without ADHD to understand how those with ADHD comprehend charts.
- We found the characteristics of people with ADHD in understanding data visualizations, which are similar to the characteristics of people without ADHD, with respect to specific visualization factors – color, text amount, and embellishment.
- We suggested design guidelines for data visualizations based on visualization literacy characteristics found in people with ADHD with the goal of helping them to better understand their data.

Chapter 2

Related Work

This chapter reviews the definition and attributes of ADHD, as well as the perception and cognition of people with ADHD. Additionally, it covers other accessible visualization works to explore and understand how to enhance data accessibility for individuals with diverse abilities.

2.1 Attention-Deficit/Hyperactivity Disorder

Attention-deficit/hyperactivity disorder (ADHD) is a neurological disorder, and the symptoms of ADHD can include inattention, disorganization, and hyperactivity-impulsivity [6, 16, 17]. Inattention and disorganization may present as being unable to focus on tasks, appearing not to listen, and losing materials when not appropriate for the individual's age or developmental level. Hyperactivity-impulsivity can manifest as excessive movement and fidgeting, an inability to stay seated, intruding into other people's activities, and having trouble waiting, when not appropriate for the individual's age or developmental level. Hyperactive-impulsive symptoms of ADHD have been shown to gradually weaken as the person ages [30]. There are different types of ADHD, and some people may predominantly experience inattention without hyperactivity, previously referred to as Attention-Deficit Disorder (ADD). It has also been documented that the inattention symptom from ADHD can manifest as the inability to shift their focus away from a particular task, known as "hyperfocus" [38]. Hyperfocus is an attention state of extreme focus on one topic or task, which can contribute to high academic and creative achievement in those with ADHD [7, 10].

Although ADHD is not considered a learning disability, it is known to co-occur with other specific learning disabilities, such as a reading or word processing disability [1, 6]. The physiology and cause of ADHD are not yet fully understood. Some evidence has been found to support a genetic link for ADHD, but its cause is not isolated to a single gene [80]. Medicine and treatment work to alter neurotransmitters, which are believed to be heavily involved with ADHD but are not proven to be the cause of the disorder. Thus, treatment often targets the symptoms of ADHD rather than the source, and it does not completely remove ADHD symptoms [23]. There is no specific biological marker that can be used to diagnose ADHD [6]. However, there does appear to be a sex-related pattern, either due to diagnostic practices or to a biological aspect of the disorder. ADHD is diagnosed more frequently in males than in females (a ratio of around 2:1 in children and 1.6:1 in adults) [6].

The need to study on people with ADHD as a user group is due to the prevalence of the disorder today. ADHD is most often diagnosed in childhood, but it is known to persist into adulthood. The estimated rate of ADHD in children around the world is $5 - 7\%$, and the rate of occurrence for adults is approximately 2.5% [23]. The percentage of college students who have ADHD in the United States is estimated to be as large as 8% [53].

2.2 Perception/Cognition of People with ADHD

There is little work on how ADHD affects a person's response to visual channels. This is partly due to the current lack of understanding regarding the specific neurological or biological causes of ADHD [80]. Studies have shown that ADHD is correlated with higher rates of self-reported vision problems but not with structural eye differences [9]. The causes for these observations remain to be explained. Although most color vision studies on ADHD focus on children, one study verified that adults with ADHD also have visual issues related to the color blue but not with red or green [44]. Another study found no hue discrimination between groups of young adults with and without ADHD, although young adults with ADHD needed more time in their color-picking task overall. The study also found that female participants without ADHD showed a faster response time than males without ADHD in discriminating red saturation, but there was no such sex difference in the other group [45].

There are many works that study reading literacy in relation to ADHD. Miranda et al. [61] discovered that adults with ADHD received significantly worse results than adults without ADHD on the metrics of reading speed and accuracy in answering questions. Coelho et al. [21] discovered similar language deficits could be found in people with ADHD regardless of their age. Contradicting these claims, Laasonen et al. [52] found that ADHD does not impair phonological skills, which are vital to reading comprehension. Alqahtani et al. [5] found that high school students with and without ADHD received similar marks in response time and quality of responses when answering questions that asked the reader to extract information from charts, tables, and paragraphs of text. They also found that people with ADHD preferred the textual paragraph over the chart despite the fact that the former form led to the longest response times and equally accurate responses [5]. With these studies in mind, this work explored general design methods to aid people with ADHD by making visualizations easier to perceive and comprehend.

2.3 Accessible Visualization

Accessible data visualizations are graphs or charts that are edited to assist people with diverse abilities in understanding data [18, 42, 43]. Increasing accessibility allows for many more people to make data-driven decisions. Among the work that focuses on creating accessible data visualizations, the largest concentration is on how to make color palettes accessible for those with low-vision and color-vision deficiencies. Kim et al. [43] defined a design model and suggested future directions for low-vision accessible visualizations based on analyzing papers from over the last 20 years. Using visualization accessibility guidelines, several methods have been developed to automatically correct images to be color-blind friendly [62, 65, 79]. There are also several accessible visualizations for people with visual impairments or blindness through various sensory substitution modalities. VOXLENS [70] is a JavaScript library to help people with visual impairments or blindness extract an overview and the details of data in online data visualization using voice-activated commands. SeeChart [4] is another tool to help people with visual impairments or blindness understand web-based data visualization by providing a summary of a chart through a natural language generator and allowing them to interact with data points through a keyboard. SVGPlott [26] is an accessible tool to create audio-tactile charts with legends and descriptions for people with visual impairments or blindness. AudioFunctions.web [3] is a web app that allows people who are visually impaired to explore charts depicting mathematical functions. It offers sonification, earcons, and speech synthesis for the exploration through mobile devices and PCs. However, Fan et al. [27] investigated the accessibility of current data visualizations on the web through an audit, survey, and contextual inquiry. They found several issues, including that many web data visualizations are still not accessible to people who are blind and visually impaired.

There are fewer works that focus on accessible visualizations for other disabilities. Reaching beyond vision-related accessibility, Elavsky et al. [25] created Chartability, a tool that allows designers and researchers to more easily analyze whether their visualization is accessible across many different disorders and disabilities. South and Borkin [74] have explored how interactive visualizations can induce seizures. From this work, accessible visualizations for those who have photosensitive epilepsy have been developed [75]. South et al. [76] also focused on exploring accessibility for those who have seizures, specifically addressing seizure-inducing Graphics Interchange Formats (GIFs) in social media. In addition, accessibility for people with Intellectual and Developmental Disabilities (IDD) was studied, including Down Syndrome, Fragile X Syndrome, Autism Spectrum Disorder (ASD), and Cerebral Palsy [85]. Wu et al. [84] conducted semi-structured interviews to identify everyday barriers that those with IDDs find when attempting to access data. Although around 20% of people with an IDD also have ADHD [51], this thesis expands upon previous research on accessible data visualizations to specifically include people with ADHD.

2.4 Guidelines to Visualization Design

Several visualization factors have been studied in the visualization community to understand how people perceive, interpret, and communicate with data in various charts and graphs.

For example, Saket et al. [67] explored several visualization methods and proposed visualization guidelines based on different tasks, including using bar charts, line charts, and scatterplots for cluster identification, correlation discovery, and anomaly detection, respectively. They also didn't recommend using line charts to identify precise data values and tables and pie charts for correlation discovery. Many studies have focused on the effects of color in data visualizations, such as the use of semantically discriminable colors for encoding concepts [63]. In addition, Szafir [78] found that perceptible color differences for points in scatterplots and lines in line charts vary inversely with the diameter of points and line thickness, respectively. She also found that colors on longer bars were more discriminable than on shorter bars of equal bar thickness. Saturation was also found to have an effect on the arousal of adults, such that more saturated color captures more attention [87].

Sibrel et al. [71] found that, when asked to identify the greatest value in a chart in which the greatest value is coded by darker colors, participants had a decrease in response time compared to when lighter colors were used to signify "more". This correlates with a bias in which people assume darker colors represent greater numerical values [69].

Designers and researchers have explored the effect of text in understanding data in visualizations. Kong et al. [47, 48] examined the influence of titles in visualizations and found that the titles that misaligned with the visualization had an impact on the visualization's perceived message, and participants recalled a visualization's message that more frequently aligned with titles than charts. Kim et al. [41] investigated the effect of captions on participants' takeaways from a visualization and found that charts have more impact on takeaways than captions. They suggested that both the chart design, such as highlighting and zooming, and the caption should work together to emphasize the same chart features. Stokes et al. [77] found that adding more textual annotations can positively influence a viewer's understanding of the data, particularly in the case of highlighting maximums or other statistical calculations.

There is a debate over the usefulness of embellishment types. It has been suggested that data visualizations should use minimal ink, avoiding unnecessary graphical elements or distractions [81].

Gillan and Richman [31] conducted two experiments to test a minimal chart using minimal ink. The results indicate that the minimal chart outperformed a traditional 2-D bar chart and a 3-D bar chart with a background image in terms of response time. In contrast, several studies have shown that embellishments can improve information retention. Borgo et al. [11] found the use of embellishments has a positive impact on memorizing information in visualizations. Borkin et al. [12] defined key factors, such as the use of color, recognizable objects, and uniqueness, that could improve the memorability of a graph. Burns et al. [15] found that using pictographs as opposed to plain bar or area charts had no negative effect on response time or accuracy. Wu et al. [85] found that replacing a chart with icons increased response times in their experiment. However, they also found that while most people with intellectual disabilities responded positively to embellished visualizations, those with autism preferred abstract ones. Therefore, even though there is a debate on whether the use of embellishments is beneficial, there is reason to study whether adding embellishments to charts helps people with ADHD to understand their data better.

Chapter 3

Factors in Understanding Charts for People with ADHD

Various types of data are generated every day, and it is necessary to understand such data properly and easily in order to make better decisions. Barriers to accessing data can have a profound effect on a person's day-to-day life. The goal of creating accessible visualizations is to help reduce these barriers to comprehending data. Understanding the specific ways that people with ADHD see charts could help to improve the accessibility of data visualizations and to support data-driven decision-making.

To understand how people with ADHD interpret data in visualizations, research goals were discussed with two domain experts who focus on neurobiological differences in ADHD. They expressed that there is little existing knowledge about ADHD's interaction with charts, but they confirmed that the goals were worth investigating due to prior research on ADHD's interaction with vision, reading, and understanding. People with ADHD, in particular, encounter the challenge of balancing attention-grabbing and focus-keeping aspects of charts with the component's ability to distract or be too stimulating [29]. Thus, conventional design practices for general audiences may result in inaccessible data communication for adults with ADHD. The experts expressed a desire for empirical research on how chart design decisions affect the chart-reading performance of adults with ADHD.

There are many different components of data visualizations that can influence a chart's readability. In this study, three chart components were selected for further study: basic color choices, the amount of text, and the use of related visual embellishments or pictographs. Because the choice of color in visualizations influence the efficiency and effectiveness of data perception [86], basic colors that are commonly used in visualizations were tested. Additionally, based on observations about the amount of text and use of visual embellishments on chart understanding [77, 85], this study tested the effects of the amount of text and the use of related visual embellishments or pictographs compared to plain charts without any text description or any embellishments, respectively. This study focuses on whether the chart literacy of people with ADHD differs from the general population with respect to specific chart design decisions and, if such a difference exists, how to create more accessible data visualizations based on those findings. In addition to functional differences due to lack of focus, people with ADHD are also known to exhibit extremely strong focus on specific topics or tasks [7]. This inability to control the object of their focus could cause a divide between design decisions that are functionally effective in boosting readability and the reader's enjoyment in the chart. Thus, when considering the equality and accessibility of charts, there are two aspects that need to be separated: enjoyment and understanding. This study also highlights whether people with ADHD tend to prefer certain charts and whether that conflicts with their ability to perform tasks or comprehend charts. Domain experts also suggested using an online survey to test the hypotheses since recruiting participants with ADHD who are willing and able to remember or arrive at in-person research labs has become more difficult since the rising use of virtual meetings.

In collaboration with domain experts and based on the following literature survey, this study tested hypotheses that consist of factors that might impact accessible visualization for people with ADHD: basic chart colors, the amount of text, the use of related visual embellishments or pictographs, and user preferences.

H1. Chart colors will differently affect response times and accuracy of those with and without ADHD Colors are used in data visualizations to encode both categorical and numeric values. The perception of color thus affects a person's ability to comprehend a chart [57]. However, ADHD is correlated with higher rates of self-reported vision problems, and these vision problems are not represented in physical eye conditions, suggesting that the issue is perceptual or cognitive [9].

Another experiment also noted that participants with ADHD had more visual problems related to blue-yellow stimuli [44]. Based on these results, it was anticipated that specific hues for charts will target those with ADHD differently.

H2. Increasing the amount of text in data visualization will negatively affect the response times and accuracy of those with ADHD Several studies have shown that ADHD affects reading ability. Adults with ADHD scored lower in reading speed and accuracy when answering questions [21, 58, 61]. In addition, people with ADHD took longer times to answer questions based on paragraphs of text than those based on charts [5]. This is further complicated by the discovery that ADHD is often found alongside other specific learning disabilities, such as a reading disorder commonly known internationally as dyslexia [6]. It was anticipated that the performances of participants with ADHD will have a negative relationship with text amount.

H3. The use of embellishments in charts will improve response times and accuracy of those with ADHD Researchers have not yet studied how the number of extra images in charts affects viewers with ADHD specifically.

When given distractions that were unrelated to the task of letter search, such as cartoon characters, participants were highly vulnerable to distraction (measured by response speed) [28]. However, participants' perceptual load was increased by images that resembled the letters they were searching for, resulting in the level of overall distraction being reduced. For those with ADHD, when individuals are faced with high levels of perceptual load, it can help improve their abilities to focus their attention [29]. These findings are also reflected when examining Intellectual and Developmental Disabilities (IDD), but the results depended on the specific IDD [85]. Due to these differences observed among IDDs and because only around 20% of people with an IDD have ADHD [51], this thesis studies whether people with ADHD specifically can benefit from different embellishment types. In this study, embellishments that represent categorical variables in data sets are used, so it was expected that the embellishments will help people with ADHD to better understand data from charts.

H4. User preferences for people with ADHD will not match the charts that result in the highest performances When considering the equality and accessibility of charts, there are two aspects that need to be separated: enjoyment and understanding. Little correlation between preference and performance has been found in the domains of musical education [50], cognitive psychology [24], and human-computer interaction [55]. Among participants with ADHD, few were shown to dislike paragraph descriptions of data sets despite the fact that this form led to the longest response times and equally accurate responses to charts [5]. A negative relationship between perception and understanding has also been found regarding the use of pictographs and icons [15, 85]. It was anticipated that these differences will be repeated in this study, and user preferences for those with ADHD will not correlate with chart components that lead to the best response times or accuracy.

Chapter 4

Study Design

A crowd-sourced study was designed to confirm the hypotheses, which involved two parts: a problem-solving task to find the differences in completion time and accuracy between groups of participants with and without ADHD and a preference task in which participants ranked charts with various chart components. Participants were asked to be as accurate as possible for the problem-solving tasks, and they were not shown the duration time of the study in order to minimize motivation for random guessing.

4.1 Stimuli

In order to create accessible graphs, which are visual forms of data communication, designers must understand how people with ADHD interact with graphs in terms of different factors. This study design focuses on three factors, which are *color*, *text amount*, and *embellishment*. Figure 4.1 illustrates examples of the stimuli used in the study.

Color. Graphs using different colors were first generated. Monochromatic ColorBrewer hues were tested since it is one of the common color palettes used in design and academia having some pre-built accessibility options for color blindness [22, 35]. Color mappings of ColorBrewer colors can also reduce contrast effects [13, 86]. In digital visualizations, *Gray*, *Red*, *Blue*, and *Green* are largely used [86]. Among them, the study focused on testing Red, Blue, and Green colors because digital displays use a combination of these three colors. Gray was used as a baseline color for the response time and accuracy measurements because grayscale colormaps have been found to be inferior for conveying value information [82].

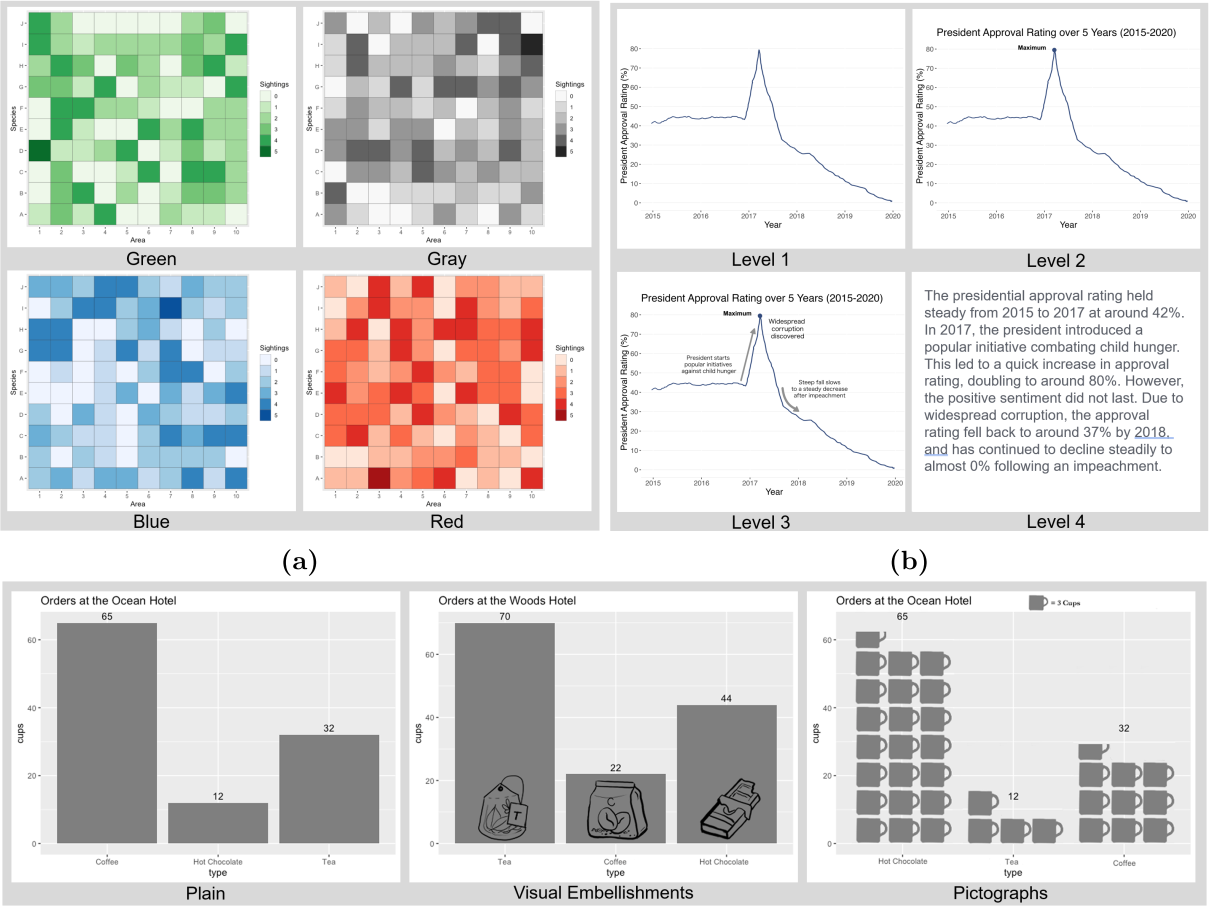
For the preference task, participants' preferences were asked only on Red, Blue, and Green colors to focus analysis on the target colors.

In the study, the lightness of each color was monotonically varied in a Heatmap (as shown in Figure 4.1a) to understand how participants interpret color mappings.

Using Heatmaps helps to study how participants perceptually and cognitively discriminate values corresponding to the lightness of a color [69]. In addition, using regularly increasing intervals of lightness in Heatmaps allows us to better control lightness and saturation shown across charts of different monochrome hues [14]. The intervals of color lightness were predefined by the discrete ColorBrewer scale, which are manually designed palettes in the perceptual color space [13]. The color palettes follow an evenly spaced sequence of lightness steps, regardless of hue. This ensures perceptual consistency between intervals, making color perception difficulty similar between trials [13].

Participants were asked to name the coordinate corresponding to the square with the lowest lightness, which would be considered to have the greatest value because people assume that darker colors are associated with larger data values [69]. A fabricated data set was used in order to lower the chances of knowledge bias and preconceived color associations. In addition, the chances that participants were simply being drawn to the largest colored area (the area-is-more bias) [68] was minimized by reducing the number of large areas with the same colors. The number of large areas was reduced by using randomized data. Finally, areas where the same values appear side-by-side were broken up with grid markings to also reduce the area-is-more bias [68].

Text Amount. This study then examined the effect of text on chart comprehension for people with ADHD. Four levels of text from the set of stimuli referring to Stokes et al. [77] were selected. Each represented an increasing number of labels: *Level 1* (a graph with only labeled axes); *Level 2* (a graph with the axes, title, and one major point labeled); *Level 3* (a graph with the axes, title, and multiple major points labeled); and *Level 4* (a paragraph of text with no chart) (Figure 4.1b). Level 1 and Level 4 were chosen to understand visualization literacy for people with ADHD in two extreme cases: a chart with only labelled axes and only text. Level 2 and Level 3 examined the effect of additional text on charts. Level 1 represents instances when only the chart is used to communicate the data, and only some context to the data is provided in the form of x and y-axis labels. The Level 2 charts added a title and one annotation to the chart. This level served to test annotations related to the



The presidential approval rating held steady from 2015 to 2017 at around 42%. In 2017, the president introduced a popular initiative combating child hunger. This led to a quick increase in approval rating, doubling to around 80%. However, the positive sentiment did not last. Due to widespread corruption, the approval rating fell back to around 37% by 2018, and has continued to decline steadily to almost 0% following an impeachment.

(a) **(b)**

(c)

Figure 4.1: Examples of the stimuli used in this study to test the effectiveness of certain chart components: (a) four different hues for the color task; (b) four levels of text for the text amount task; and (c) three types of charts for the visual embellishment task – a bar chart without any embellishments (left), use of visual embellishments (center), and using icons in pictographs (right).

main idea of the chart, and charts in level 2 had an average of 21.5 words. Level 3 added more textual annotations and highlighted major trends in the data, such that a large portion of the white background space of the graph was covered in annotations. Participants using Level 3 charts would have to identify which pieces of text are not relevant to the task. These charts had an average of 35.5 words. The Level 4 charts evaluated whether an entirely textual representation of the data without a chart would be best for those with ADHD. Stimuli from Level 4 used an average of 47 words. The levels were labeled such that the value increases as the amount of text used increases.

All stimuli are adapted from the work of Stokes et al. [77], which used univariate line charts because they are commonly used and are easily annotated. The charts were all generated from synthetic datasets and annotated by a data visualization expert, aiming to emulate realistic but simple graphics. Standard practices, including lightening axis ticks and gridlines, were used in the design of stimulus in order to maintain focus on the line [77].

Embellishment. This study then analyzed how visual embellishments and pictographs affect the chart understanding of people with ADHD. The goal was to examine whether those with ADHD are faster at analyzing less "cluttered" designs or charts with more images, due to the benefit of increasing perceptual load. To do this, three different embellishment types were tested: *plain bar charts*, *bar charts with individual images or visual embellishments*, and *pictographs* (icons) (Figure 4.1c), as these chart types were examined in Wu et al. [85] under their visual embellishment experiment. Pictographs and charts with visual embellishments were chosen for their ability to engage readers and to improve recall and information finding [11, 34]. Plain bar charts were gray bar charts with no visuals added to the design. Bar charts with visual embellishments were gray bar charts with a single black image added onto the face of the bars, acting as a representation of the categorical variable. For example, an icon of a chocolate bar was used as a visual metaphor for "hot chocolate". Pictographs were bar charts in which bars were replaced with stacks of icons representing categorical variables. Each icon represented a set fraction of the value of the overall bar. For this task, in order to investigate the min/max and ratio questions, at least more than two categorical variables needed to be represented in the stimulus bar charts. Thus, each trial required charts with a minimum of three values. Based on this requirement, the study was designed such that participants view each bar chart with three values to reduce participant frustration and balance the task's difficulty, following the stimuli creation of Haroz et al. [34]. Bar charts were chosen for their simplicity in design in order to easily highlight the meaning of the visual embellishments. They were also chosen for their parallel similarity to pictographs; such pictographs are most often depicted in bar-like stacks, where the height or width of the stacks represent values [34].

Currently, customized images created by artists and designers, which are later added to graphs, still fall under the umbrella of visual embellishments [64]. The embellishments used in this study were created by an artist. All images and icons were relatively simple, consisting of one consistent lightness of gray for line work or to fill the icon. A gray-scale color scheme was used to minimize compounding factors in color choice. This removed the possibility that the participant was distracted by any color choices used to encode meaning.

4.2 Task

Participants performed three tasks. To reduce participants' frustration and the number of participants who do not complete the task due to the difficulty of the task, multiple-choice questions were used for the text amount and the embellishment tasks. Multiple-choice questions also allowed us to easily assess response time and accuracy. In a preliminary study, it was found that the order of task complexity is color (the easiest), amount of text, and embellishments (the most challenging). The study design repeated the color and amount of text tasks 2 times and the embellishment task 3 times to obtain robust results. At the end of each task, participants were asked to rank their visualization preferences, depicted with the various chart components (e.g., the same chart shown in different colors for the first task). The participants were then asked to share their reasoning in a free-response box.

Color: In the first task, colors were tested in Heatmaps. Similar to a previous color study [69], the stimulus Heatmaps used in this study represented a grid of ten zones of a fabricated planet's ocean crossed with sightings of ten different animal species.

The lightness of the color of squares represented the values of the squares. Participants were asked to identify the coordinates corresponding to the greatest value in each grid. Each color was tested twice. This resulted in eight color questions (4 colors × 2 repeats).

The task of searching for the greatest value in a graph was chosen because it allows measurement of participants' ability to extract the greatest value, the darkest color, without needing to understand the context. It is also a popular color mapping test [69, 71]. This task focused on studying how color affects the visualization-reading performance of participants, using the metrics of accuracy and response time. The results of this task can tell us more about whether people with ADHD have different cognitive and perceptual differences to color in the context of graph reading.

Text Amount: In the second task, participants were shown line graphs annotated with various levels of text. Participants were then asked to answer a multiple-choice question for trend estimation related to key takeaways from the graph (e.g., "Around which year started the largest increase in immigration?"). This resulted in a total of eight questions, two questions for each level (4 levels × 2 repeats).

The goal of this task was to have participants examine and understand trend shifts in the line charts/text.

The study aimed to test trend identification for the time series data because the skill is useful in understanding overall patterns in various time-series data, and it is a common task in time series analysis [40, 85]. The main goal of this section was to test whether various text amounts aid or hinder the visualization-reading performance of participants.

Embellishment: Finally, for the task testing visual embellishments and pictographs, participants were asked to answer multiple-choice questions on three different types of questions. In the study, the participants were asked to answer the following three types of questions for each chart type:

1. *Search* questions asked participants to find the value associated with a category (e.g., "How many cups of coffee were ordered?")

2. *Ratio* questions asked participants to make judgments of relationships based on values and area sizes of the graphs (e.g., "Which activity receives less than 25% of screen-time?")

3. *Min/Max* questions asked participants to find the largest/smallest value in the charts (e.g., "What type of activity do people spend the most time on while using their phones?").

Participants were not made aware of the different question types. This section contained 27 questions (3 chart types × 3 question types × 3 repeats).

An array of pictographs can communicate small quantities effectively, as compared to bar charts [54, 59]. Thus, the Search question was chosen to test the value estimation of a specific category for bar charts. An array of pictographs can also be used to represent the relationship between parts and the whole [15]. To understand how this choice impacts the insights that people with ADHD gather from charts, the Ratio question was used. Additionally, in visualization, locating and reporting specific data is one of the tasks used to measure reader's understandability [15]. The Min/Max question was used to estimate this aspect.

Measuring understanding is a complicated task often replaced by analyzing free-response answers [15], response time, and accuracy [11]. In this study, response time and accuracy were used as objective measurements for understanding. In order to better understand how to create accessible data visualizations for those with ADHD, both preferences and objective measurements were recorded for each of the tasks. This study examined whether there is a significant difference between the preferences of participants with and without ADHD.

4.3 Data Generation

To control the characteristics of the visualizations, synthetic data was used. For the text tasks, the line charts used were created by Stokes et al. [77]. Each graph used an equally complex synthetic data set, ensuring that a difference in responses between trials would be due to a difference in the chart text rather than to the complexity of the data shown. In the color tasks, integers from 0 to 4 were randomly generated for a 10 × 10 grid. One of the coordinates was randomly increased to 5 as the testing coordinate. For the visual embellishment and pictograph tasks, data sets were created, inspired by those used in Borgo et al. [11]. Each bar chart consisted of three categorical variables with small random values (less than 300) since the categorical variables represented everyday physical items such as drink orders.

For each data set, the order of categorical variables was rotated between the chart types (plain bar chart, chart with visual embellishments, or pictograph). The values were slightly increased or decreased, but the relative height of the bars to one another stayed the same. This was to help control for visual search based on the categorical variables and actual content, mitigating possible changes to response time based on changing heights of the bars between chart types.

The charts shown when participants were asked to share their preferences were selected to be similar to a real-world visualization. Since the color tasks used the context of a fake alien planet, the charts that were shown to ask for participants' preferences on color were constructed from the Seaborn "flights" dataset [83]. The text preference charts had the context of presidential approval ratings, and the embellishment type preference charts had the context of drink orders at a hotel.

4.4 Participants

This study recruited a total of 160 participants, through Prolific [66], 80 each for the group with ADHD (ADHD group) and the group without ADHD (Non-ADHD group). Screening questions were used to ensure that the participants were at least 18 years old, had ADHD for the ADHD group and did not have ADHD for the Non-ADHD group, and were fluent in English. Responses were filtered such that only those with normal or corrected to normal vision, including color-blindness, were included in the experiment. This removed 10 participants with ADHD and 3 participants without ADHD. Overall, the final data set includes 70 participants in the group with ADHD and 77 participants in the group without ADHD. Participants were given the title of the survey as well as a short description of its goal and expected tasks. Across both groups, participants took an average of 22 minutes to complete the survey. They were offered an average rate of \$8/hr or around \$0.14/min as compensation. The ages of all participants ranged from 18 to 54. In the group with ADHD, there were 30 female and 40 male participants (using sex assigned at birth). This showed that the sample population followed the general ADHD population, where more males than females are diagnosed with ADHD [6]. The largest represented age group was 18 - 24. In the group without ADHD, there were 38 female and 39 male participants. The largest represented age group was also 18 - 24. Participants also shared information on their education level, which is included in Appendix A (Figure A.1).

4.5 Procedure

In order to take part in the survey, participants were grouped by ADHD (ADHD group and Non-ADHD group). The pre-screening was performed through Prolific. Participants were asked whether they have attention deficit disorder (ADD) or attention-deficit/hyperactivity disorder (ADHD) to confirm their eligibility for the study. The study was conducted as approved by the OU Norman Institutional Review Boards (IRB). Participants were given a consent form. After giving their informed consent, participants were asked a series of demographic questions. The tasks were then given in the following order: Color (8 text response questions and preference rankings), Text Amount (8 multiple choice questions and preference rankings), and Visual Embellishments and Pictographs (27 multiple choice questions and preference rankings). The order of tasks was not counterbalanced. To help participants prepare for the more challenging tasks, tasks were ordered according to their level of difficulty found in a preliminary study, with the hardest task placed last. Prior to each task section, an instruction page and a sample question and answer were provided. After completing all the tasks, the participants could leave any comments.

The design of this study addressed two possible areas of bias: the order of questions (Ordering bias), and tiredness (Attention bias) [11]. Between participants, the order of questions was randomized for each task. This aimed to help prevent ordering bias, the possibility that answering questions becomes easier after more practice. Randomizing also helps to mitigate the effects of attention bias in the results, in which a participant's fatigue in doing the same task could affect their responses to the later questions.

4.6 Data Analysis Methodology

Across all three experiments, the response time data was normally distributed after using Tukey's Ladder of Powers transformation. Additionally, the data had a homogeneity of variances. Thus, I performed Analysis of Variances (ANOVAs) on the data. For the color and text amount experiments, I performed a two-way 2×4 ANOVA with two groups (people with and without ADHD) and four factors (color: four colors, text amount: four text levels). For the embellishment experiments, I used a three-way $2 \times 3 \times 3$ ANOVA with two groups (people with and without ADHD), three question types, and three embellishment types. The Tukey p-value adjustment method was used for post-hoc analysis. For the accuracy data, I did not use ANOVA tests since the response variable was either 0 or 1. I created generalized linear mixed models (GLMM) on a binomial distribution. This experiment used two/three repetitions for each experimental condition. For each result, I computed an average response time and accuracy per subject per condition. In all tests, we adjusted for randomized error between participants, ensuring that we were not treating responses from the same participant as independent. Finally, to analyze preference data, I used chi-squared tests and the Bonferroni Adjustment as a post-hoc analysis on the significant results. Since participants were asked to rank their preferences in an ordinal manner, a singular blank response from a participant was filled in with the remaining number. The results from these tests are discussed in the next section.

Chapter 5

Results

5.1 Color

5.1.1 Objective Measurements

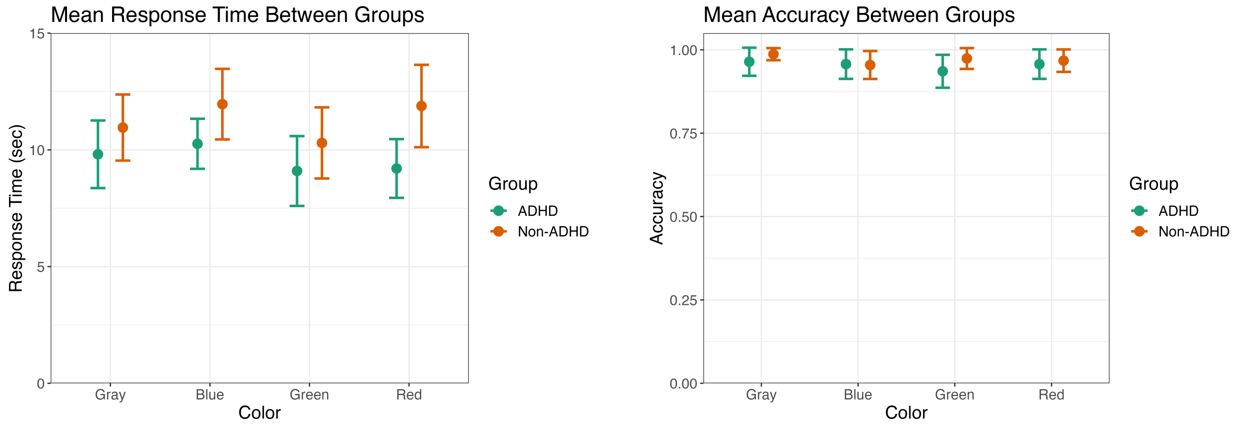
The average response times during the color task for the group with ADHD and without ADHD were 9.59 ± 0.62 seconds (95% confidence interval) and 11.23 ± 0.70 seconds, respectively (Figure 5.1a). The average accuracy scores for the group with ADHD and without ADHD were $95.36\% \pm 0.04\%$ and $97.08\% \pm 0.02\%$ (Figure 5.1b).

The results of the tests revealed a significant effect of ADHD ($F(1, 145) = 4.55$, $p = 0.035$) and color ($F(3, 143) = 10.16$, $p < .001$) on response time. There was no significant interaction between ADHD and color. Those with ADHD were significantly faster at the color task than those without ADHD, across all hues ($p = 0.03$).

Participants performed the slowest on average with the graphs using blue ($11.1s \pm 0.84s$), and they performed the fastest on average with green ($9.72s \pm 0.99s$). Green charts had significantly the fastest responses averaged across both groups ($p < .001$). Both groups completed the color task with a mean of at least 94%, and neither color nor ADHD was a significant predictor for accuracy.

5.1.2 Preference Measurements

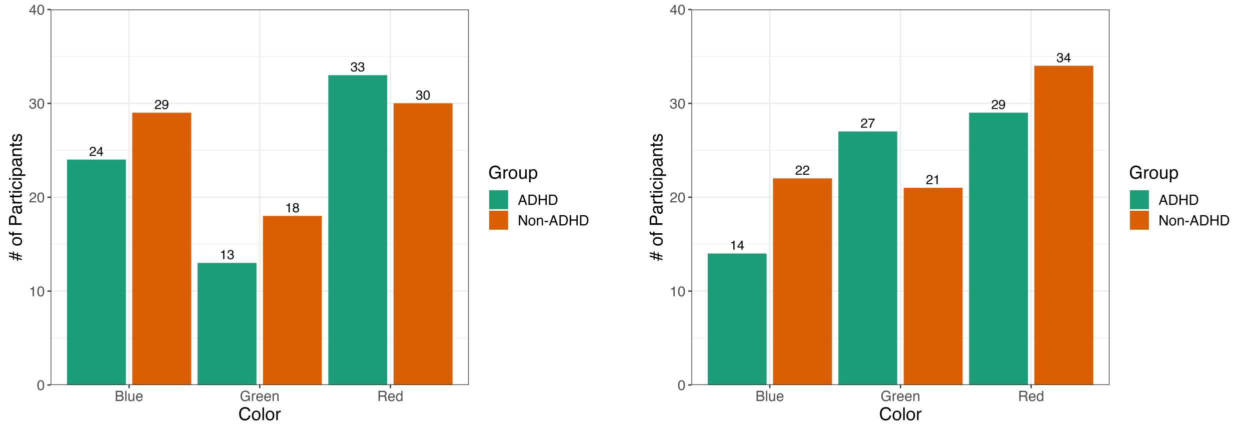
There were no significant differences when testing the highest, middle, or lowest-ranked hue preferences between the group with ADHD and the one without ADHD. However, there were differences in color preferences within each group. There was a significant difference in color preference for the group with ADHD ($\chi^2(4, N = 210) = 29.49$, $p < .001$). In post-hoc



(a) Response Time

(b) Accuracy

Figure 5.1: (a) Mean response time and (b) accuracy with 95% CI for different hues (Blue, Gray, Green, and Red). Analysis compared the group with ADHD (green) and the group without ADHD (orange).



(a) Highest Ranked

(b) Lowest Ranked

Figure 5.2: (a) Favorite and (b) least favorite rankings of hues by the group with ADHD (green) and the group without ADHD (orange).

analysis, it was revealed that red was significantly favored over green ($p < .001$) and over blue ($p < .001$) (Figure 5.2a). For this group, red was most likely to be chosen as the favorite color, but it also was most likely to be chosen as the least preferred color. It was polarizing.

The group without ADHD also showed a significance difference ($\chi^2(4, N = 231) = 19.714$, $p < .001$) between red and green ($p < .001$). Both groups had the smallest number of participants who voted green as their favorite color. However, the group without ADHD was much more likely than the one with ADHD to vote red as their least favorite color over green (Figure 5.2b). Unlike the group with ADHD, the group without ADHD did not have a significant difference between red and blue preferences.

26 participants with ADHD and 26 participants without ADHD stated that they picked the chart colors that were easiest to look at. Participants with ADHD may have preferred the red chart because they found it perceptually easier to view. Participants with ADHD noted “I like blue the most, but in the red one is easier to differentiate (P48, ADHD)” and “I feel like the green chart is the most [difficult] to read, the colors [are] too similar to me. The blue one is better; it has more contrast, but for me, the red one is the most accessible to read, the contrast between colors is great, and it is overall the clearest (P58, ADHD).” Notably, one participant differentiated ease of perceptual observation from how pleasant the chart's color was to physically view, stating, “I feel the red shows the difference most clearly. However, the blue is right behind and is more pleasing to the eyes (P64, ADHD).” Participants from the ADHD group may have also preferred the red chart due to its ability to grab their focus and attention. One participant with ADHD said, “Red is a more vibrant color and catches my attention easily (P38, ADHD).” However, as mentioned before, many of the participants with ADHD voted red as their least favorite chart color. This may be due to emotional associations with the color red. Color chart preferences were often tied to aesthetic reasons, as seen in the statements “Green is pleasant, red is unpleasant, blue middle ground (P13, ADHD)” and “Red is too shocking (P19, ADHD).”

In both groups, the green chart received the fewest votes for being participants' favorite chart. This may be because some participants chose chart colors based on cultural and personal context, such as prior experience with using that color in visualizations (“I think the worst scale is the green one, and that might be because it's not a common scale for me to visualize in that color (P46, Non-ADHD)”) or general experiences with the color (“Every graph is readable so I ranked them in order from my favorite to least favorite color (P21, ADHD)”). For the ADHD group, the green chart may also have been overlooked for the same reason that red was preferred: green was not as effective in grabbing the participant's attention. One participant with ADHD said, “Red is easier to see, and it makes me pay more attention. Blue is nicer on the eyes and still provides enough contrast. Green doesn't make me pay as much attention as the others (P3, ADHD)”.

5.2 Text Amount

5.2.1 *Objective Measurements*

The average response times for the group with ADHD and the group without ADHD were 30.61 ± 2.76 seconds (95% confidence interval) and 34.13 ± 2.62 seconds, respectively (Figure 5.3a). The mean accuracy for the group with ADHD was $84.64\% \pm 0.05\%$, and the mean accuracy for the group without ADHD was $78.08\% \pm 0.05\%$ (Figure 5.3b).

There was a significant effect of ADHD on response time ($F(1, 145) = 4.06$, $p = 0.05$) and of text amount on response time ($F(3, 143) = 158.14$, $p < .001$) with no significant interaction between ADHD and amount of text. Those with ADHD were significantly faster at answering the text amount task than those without ADHD across all text levels.

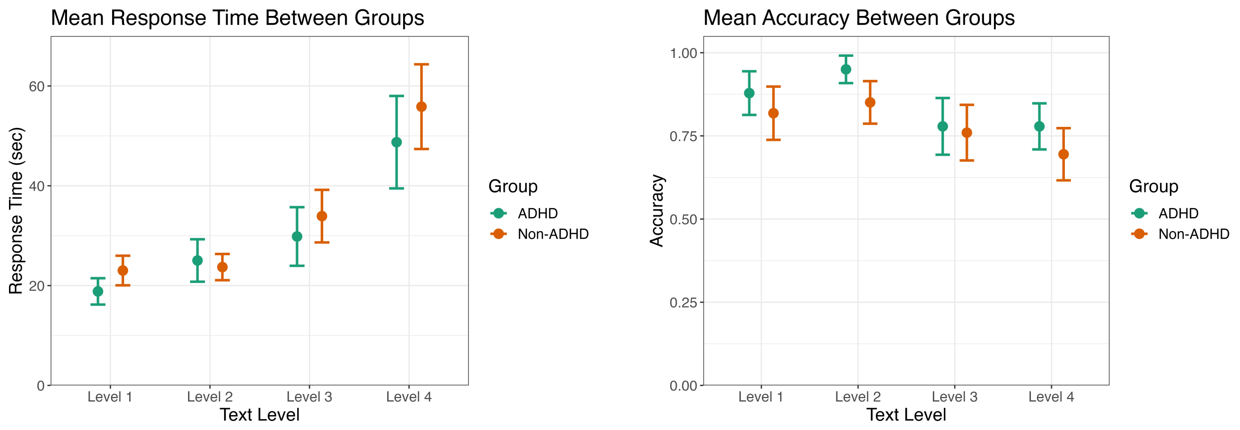
The results also show that participants had the fastest responses when using Level 1 charts ($21.0s \pm 1.72s$).

An increase in the amount of text used in a chart significantly increased response time (Level 1 faster than Level 2: $p = 0.026$, Level 2 faster than Level 3: $p < .001$, Level 3 faster than Level 4: $p < .001$).

Level 1 text amount significantly affected the accuracy of responses ($p = 0.048$). Responses for the Level 1 charts ($84.7\% \pm 4.12\%$) were significantly more accurate ($p = 0.006$) than the responses for the paragraphs of text (Level 4) ($73.5\% \pm 5.06\%$). Level 2 had the highest average accuracy ($89.8\% \pm 3.47\%$), but there was no significant difference in accuracy between responses using Level 1 and Level 2 charts.

5.2.2 *Preference Measurements*

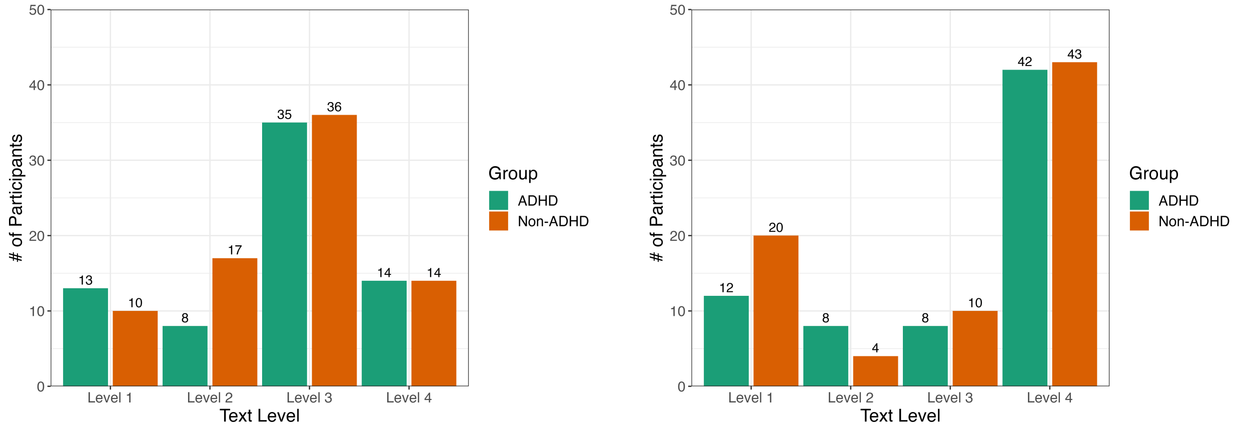
There was a significant difference in preference for text amount within those with ADHD ($\chi^2(9, N = 280) = 104.8$, $p < .001$). Overall, the greatest number of participants ranked Level 3 charts as their favorite, and the least number of participants rated Level 2 charts as their favorite (Figure 5.4a). With further analysis, it was revealed that there were significant differences in preferences between Level 1 and Level 3 ($p = 0.008$) and Level 1 and Level 4 text amounts ($p < .001$), with Level 1 being preferred over Level 4. They also had significant differences in preference between Levels 2 and 3 ($p < .001$), 2 and 4 ($p < .001$), and 3 and



(a) Response Time

(b) Accuracy

Figure 5.3: (a) Mean response time and (b) accuracy with 95% CI for text amount level. Analysis compared the group with ADHD (green) and the group without ADHD (orange).



(a) Highest Ranked

(b) Lowest Ranked

Figure 5.4: (a) Favorite and (b) least favorite rankings of text amounts by the group with ADHD (green) and the group without ADHD (orange).

4 ($p < .001$). There was no significant difference in preference between Level 1 and Level 2. Similarly, a majority of the group of participants without ADHD ($\chi^2(9, N = 308) = 89.40$, $p < .001$) also ranked the Level 3 charts as their most favorite (Figure 5.4a). However, they also had a significant preference for Level 2 charts over Level 1 charts ($p = 0.01$), which was not seen in the group with ADHD. There were no significant differences between the groups when testing individual rankings for the first, second, third, or fourth rankings.

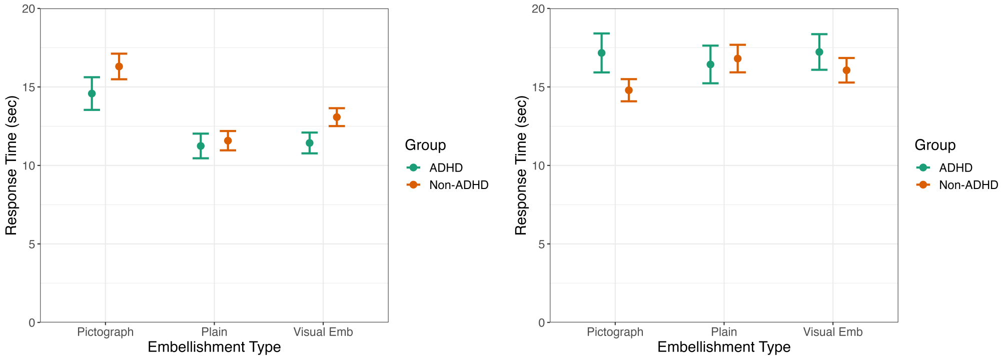
Participants preferred Level 3 charts the most because the full context given by the extra-textual annotations was viewed as helpful and relevant. A participant with ADHD said, “[The Level 3 chart] provides the most information in the most visually appealing way and makes it very clear to read (P29, ADHD)”, and a participant from the Non-ADHD group, who ranked the Level 3 chart as their favorite, said, “I like information, the more the better. I like context and visualization to work together to give me details (P43, Non-ADHD).” Participants from both groups ranked the Level 4 stimulus as their least favorite because they found it “difficult” to comprehend due to the lack of visual aids. One participant from the ADHD group said, “The text in [Level 4] would be my least preferred choice as I simply find it difficult to visualize and have to read it over twice to fully grasp the information (P29, ADHD)”, and a participant from the Non-ADHD group said, “I find it more difficult to sort the helpful data from a lot of information. It is easier to see in a chart or diagram (P77, Non-ADHD).”

23 participants with ADHD and 17 participants without ADHD cited that they selected charts based on how easy they were to read or comprehend, and 9 participants with ADHD and 7 participants without ADHD described that there needed to be a balance between enough detail and too much detail in the chart textual annotations. However, this balance and opinion on which chart was “easiest” to read differed between the two groups. Participants in the group without ADHD found that the Level 2 chart was preferable to the Level 1 chart because it balanced between detail and simplicity. One participant noted, “Level 2 chart wins over [the Level 1 chart] mainly because it has information (displayed through a title) that also helps read the data (P12, Non-ADHD).” In contrast, more participants with ADHD preferred the Level 1 chart over the Level 2 chart because they did not feel that the text on the Level 2 chart provided significant information. One participant stated, “The maximum point in [the Level 2 chart] is unnecessary and feels patronizing. It’s better to have nothing (P69, ADHD).”

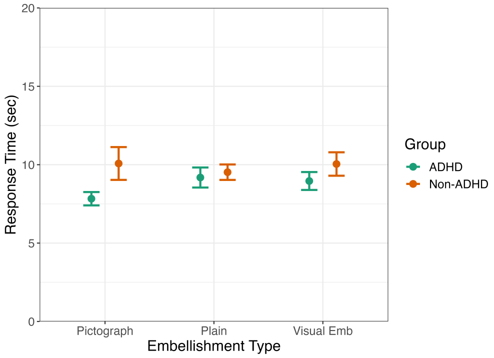
5.3 Embellishment Types

5.3.1 Objective Measurements

During the tasks that tested the use of visual embellishments and pictographs, the mean response time was 12.67 ± 0.61 seconds (95% confidence interval) for the group with ADHD



(a) Search Questions **(b)** Ratio Questions



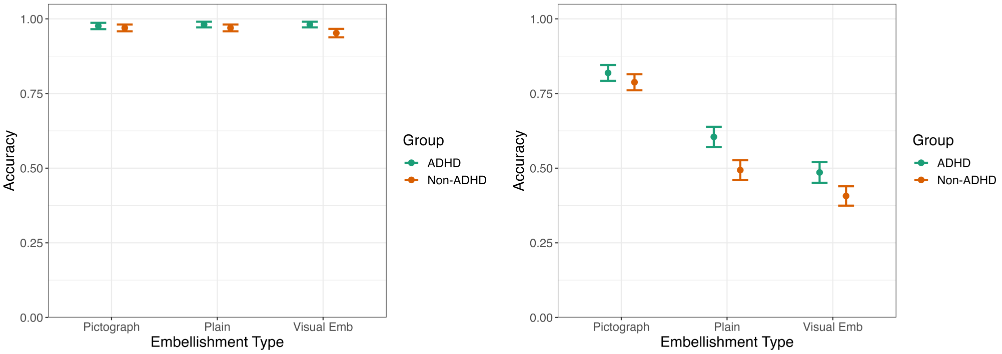
(c) Min/Max Questions

Figure 5.5: Mean response time with 95% CI for each question type: (a) Search, (b) Ratio, and (c) Min/Max Questions. The study used bar charts with different embellishment types: a pictograph, a plain bar chart (Plain), and a bar chart with visual embellishments (Visual Emb). Analysis compared the group with ADHD (green) and the group without ADHD (orange).

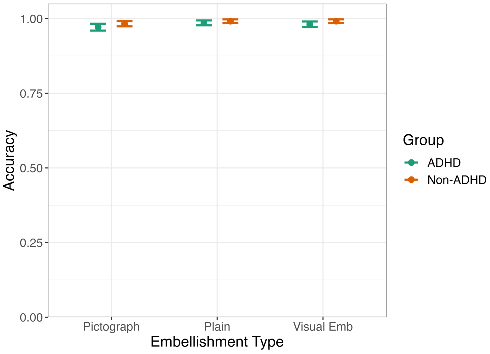
and 13.14 ± 0.51 seconds for the group without ADHD (Figure 5.5). The mean accuracy was 86.51% ± 0.03% for the group with ADHD and 83.84% ± 0.02% for the group without ADHD (Figure 5.6).

There was a significant effect of question type on response time ($F(2, 144) = 389.32$, $p < .001$) and of ADHD on response time ($F(1, 145) = 4.92$, $p = 0.03$). Participants with ADHD were significantly faster at answering the questions for this task than participants without ADHD when times were averaged across questions and embellishment types.

There was no significant interaction between ADHD and embellishment type nor interactions among all three of these factors. However, there was a significant interaction between question type and embellishment type ($F(4, 580) = 24.66$, $p < .001$). For search questions, pictographs



(a) Search Questions **(b)** Ratio Questions



(c) Min/Max Questions

Figure 5.6: Mean accuracy with 95% CI for each question type: (a) Search, (b) Ratio, and (c) Min/Max. The study used bar charts with different embellishment types: a pictograph, a plain bar chart (Plain), and a bar chart with visual embellishments (Visual Emb). Analysis compared the group with ADHD (green) and the group without ADHD (orange).

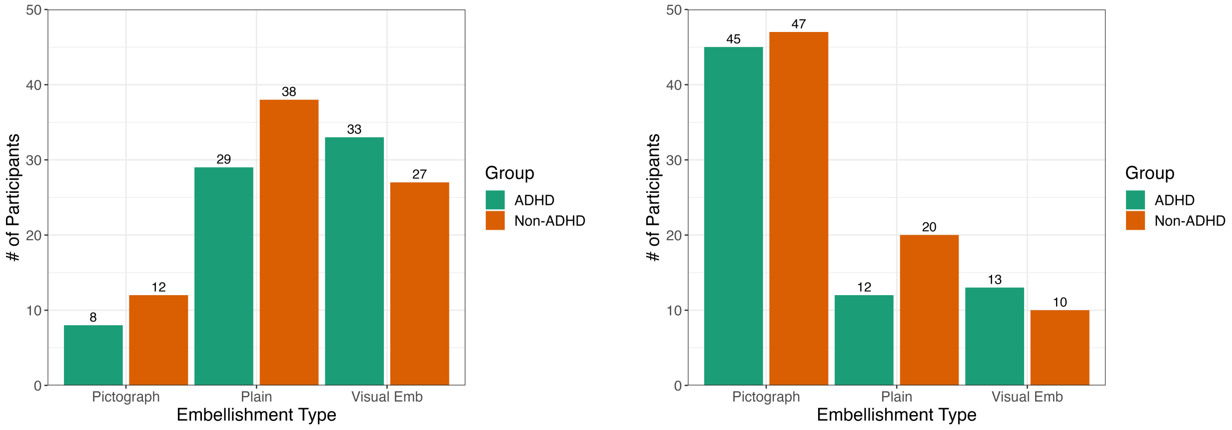
$(15.5s \pm 1.28s)$ significantly slowed participants' response times ($p < .001$) compared to plain bar charts $(11.4s \pm 0.97s)$. A significant decrease in response time ($p < .001$) was also seen when comparing pictographs against bar charts with visual embellishments $(12.3s \pm 0.85s)$. The charts with visual embellishments also had significantly slower response times ($p = 0.002$) compared to those of the plain bar charts. For min/max questions, pictographs $(9.01s \pm 1.15s)$ significantly improved response times ($p = 0.006$) over plain bar charts $(9.36s \pm 0.78s)$. Similarly, pictographs also significantly improved response time ($p = 0.002$) compared to bar charts with visual embellishments $(9.53s \pm 0.94s)$. There was no difference between plain bar charts and charts with visual embellishments for those questions. For ratio questions, none of the charts were associated with significant differences in response time for either group.

Similar to that of response time, analysis revealed that question type is a significant factor on accuracy ($p < .001$). There was an interaction between the question types and the chart's embellishment type ($p < 0.03$). The two groups had no significant differences between them in terms of accuracy for this task. For min/max and search-type questions, there was no significant difference on accuracy whether plain charts, charts with visual embellishments, or pictographs were used. The ratio questions were the most difficult to answer for both groups (Figure 5.6b), and participants responded significantly more accurately $p < .001$) with Pictographs ($80.3\% \pm 3.72\%$) than with the plain bar charts ($54.6\% \pm 4.65\%$). They also performed significantly better ($p < .001$) with plain bar charts than with the charts using visual embellishments ($44.4\% \pm 4.64\%$).

5.3.2 Preference Measurements

There was a significant difference in preference for embellishment type within the group with ADHD ($\chi^2(4, N = 210) = 48.77$, $p < .001$) (Figure 5.7). Specifically, pictographs were significantly ranked the lowest compared to the other two embellishment types ($p < .001$). There was no significant difference in preference between plain bar charts and bar charts with visual embellishments. Similarly, there was a significant difference among the rankings in the group without ADHD ($\chi^2(4, N = 231) = 53.84$, $p < .001$). They also ranked pictographs significantly lower than the other two charts ($p < .001$). However, the group without ADHD saw a significant difference in preference for plain bar charts over bar charts with visual embellishments that was not seen within the group with ADHD ($p = 0.005$) (Figure 5.7). There were no significant differences between the groups when testing individual rankings for the first, second, or third rankings.

16 participants with ADHD and 16 participants without ADHD noted that they did not like the charts with visual embellishments or the charts with pictographs because they were too "cluttered", "busy", or "confusing". One participant from the ADHD group said, "[The chart with visual embellishments] was simple, but the graphic was helpful. There was no visual clutter. [The plain bar chart] required me to read into the values and legend, but it wasn't cluttered. [The pictograph] felt horrible for me, as it was too distracting to obtain the valuable data instantly (P31, ADHD)." A participant from the Non-ADHD group



(a) Highest Ranked **(b)** Lowest Ranked

Figure 5.7: (a) Favorite and (b) least favorite rankings of plain bar charts, bar charts with visual embellishments, or pictographs by the group with ADHD (green) and the group without ADHD (orange).

commented, "[The plain bar chart] has all the info you need, [the chart with visual embellishments] has some pictures that I don't really feel they belong there and [the pictograph] is just distracting (P51, Non-ADHD)."

A possible explanation for why the group with ADHD had no significant difference in preference between the plain bar charts and charts with visual embellishments is that they found that the images from the visual embellishments to be closely connected to the chart's meaning, making their tasks easier. One participant noted, "[The chart with visual embellishments] is more precise and faster to recognize each item, [the plain bar chart] is the same but with less detail, [the pictograph] has too much going on, it's interesting but not intuitive (P40, ADHD)."

Chapter 6

Discussion

This study found that the participants with ADHD completed all tasks faster than those without ADHD. These results may be explained by the activation of hyperfocus, a state of high focus and attention [7, 32]. It has been studied that those with higher numbers of symptoms related to ADHD also have more frequent hyperfocus events across studying, hobbies, and screen time [39]. Since participants of this study had told the purpose of the survey, it might have activated their interest or competitiveness, a necessary component for the activation of hyperfocus [10].

This heightened state of focus can explain why the group with ADHD performed tasks faster than the group without ADHD. It also could account for the similar levels of accuracy between the two groups' responses, but this result comes as less of a surprise since it has been previously recorded that students with ADHD produce similar quality responses to those without ADHD when answering data-driven test questions [5]. Despite the findings that those with ADHD were faster than those without ADHD overall, there was evidence that specific chart components did not affect the performances of participants with ADHD differently than those of participants without ADHD. From these results, following preliminary guidelines were created.

Use similar colors for both people with ADHD and without ADHD: Hypothesis **H1** was **not supported**. Best-practice hue design decisions for a general audience may be applied to audiences that include adults with ADHD. Chart colors do not appear to interact differently with symptoms of ADHD. The lack of difference in performance between the groups for the color blue is supported by previous research; several works have found a lack of difference in hue discrimination between participants with and without ADHD [45, 46].

It was discovered that attention significantly increases the perception of the color blue for both groups, but that does not cause a difference in blue perception between the two groups because those with ADHD have intact covert attention, the ability to pay selective attention to competing stimuli without moving one's eyes [46]. The study that found a difference in blue-yellow vision for adults with ADHD explained that a deficiency in dopamine within the central nervous system of those with ADHD may cause differences in the retina [44]. Since some participants may have been taking medication at the time of the study, the participants may not have had a dopamine deficiency, contributing to why the results saw no difference in hue discrimination between the groups.

The results revealed that many participants in both groups preferred red heatmaps over blue. When asked to provide more explanation for their choices, those with ADHD explained that they were drawn to colors that were more attention-grabbing, such as "red is easier to see, and it makes me pay more attention (P3, ADHD)." Others mentioned the hue's effect on perceived contrast: "all the hues have good contrast and are readable (P8, ADHD)" and "for some reason, the contrast between the highest and second highest colors is best in red (P11, ADHD)." Likewise, participants without ADHD said, "Red has a bigger contrast, blue is a color that blends well together, and the lighter colors of green are harder for me to distinguish (P12, Non-ADHD)" and "I think that there is more contrast in the red, followed by the blue and then the green which makes it easier to read the data (P4, Non-ADHD)." These similarities in preference may be related to why the groups performed similarly in the hue tasks. Yet, these preferences do not correlate with the hue that led to the best response times in the results, which was green for both groups. Therefore, further work may need to be conducted to understand the relationship between user performance and preferences.

In this study, color did not affect the response time or accuracy of participants with ADHD differently from the control group. This is a positive discovery as it opens the number of colors that can be used to encode meaning in charts.

Use a graph with a minimal text annotation: Hypothesis **H2** was **supported**. General guidelines for the amount of text annotation on charts may be applied to audiences that include adults with ADHD. Text annotations on a chart that are not relevant to the task can negatively affect response times and accuracy. Increasing the amount of textual annotations on charts appeared to negatively impact the response time of those with ADHD without significantly increasing their accuracy. In this study, both groups performed significantly faster using the chart with the fewest annotations (Level 1) as opposed to the other text levels (Level 2-4). It was also found that participants had significantly more accurate responses when using the graph with minimal text annotations compared to the paragraph of text.

This is supported by previous research that adding text to a chart can significantly affect the type of information and takeaways that viewers find from the data; it was found that viewers are not likely to take away information that is not included in the annotations [77]. In this study, each participant was asked to answer one question pertaining to a major takeaway of the charts. Therefore, any text not related to that question may have become irrelevant to the task. The study design did not always ask a question directly outlined by the labels in the charts. For the paragraph of text (Level 4), many more words were available to act as distractors. This may explain why participants were significantly faster when using the plain line chart (Level 1) than the charts with other text amounts (Level 2-4). A previous study found that an attention-distractibility trait, measured by slow response time, significantly increased with irrelevant visual cues [28].

This study found evidence that those with and without ADHD perform similarly despite the number of textual annotations on a chart. Previous work has also found that those with ADHD showed no difference in phonological processing [52] or in written test-taking response time [5]. Additionally, the attention-distractibility trait was found in general audiences regardless of the severity of ADHD symptoms present in a participant [28]. Therefore, those without ADHD may be just as susceptible to irrelevant textual distractors as those with ADHD.

In certain cases, text deliberately integrated and placed in the right semantic context can support visual images to improve a viewer's understanding [37]. The Level 3 chart was voted as the most preferred chart type by both groups. Like the color preferences, there seemed to be a disconnect between participants' preferences of text amount and the effectiveness of the design choice (based on accuracy and response time). Participants with ADHD chose the Level 3 chart because "it provides additional context that keeps me interested and makes it easier to remember the data produced (P11, ADHD)" and it "had an extensively detailed amount of info on it to divulge [a] more useful statistic visual (P49, ADHD)." Since the preference charts were not associated with an explicit question to be answered, some found that the highlight of the "maximum" point in the Level 2 chart was irrelevant. One person said it "felt out of place (P54, ADHD)", and another participant called it "unnecessary information (P20, ADHD)." As seen in these comments, more text may be helpful in understanding the context of the graph, but including extra information unrelated to the question or task at hand impeded the participants, despite their interest in the extra information.

This study showed that extraneous text can be similarly distracting for both groups if the task does not directly match the text, causing significant decreases in response time. Therefore, this guideline recommends minimal use of text when designing charts for general audiences, including those that contain people with ADHD, especially if the text is not vital to the message that the designer would like to communicate. This guideline only applies to data visualizations created for audiences with the goal of communicating an idea rather than visualizations created for data exploration. As can be seen in the participants' comments, more textual information may help when trying to understand a broader view of the data.

Use pictographs for ratio-type and min/max-type questions and plain bar charts for search-based questions: This study's findings suggested that hypothesis **H3** is **partially supported**. General guidelines for chart type apply to both groups, but it depends greatly on the task types. Pictographs are the best for ratio-type questions and for min/max-type questions; plain bar charts are the best for search-based questions.

Although there is a debate on whether the use of embellishments is beneficial, the use of pictographs improved the response times of participants with ADHD in the min/max questions and improved accuracy in the ratio questions.

In addition, plain bar charts help those with ADHD understand data in the search questions.

Similar to the text-based tasks, an increase of visual stimuli used in a chart may be useful only if the images increase the perceptual load of the viewer; that is, the amount of task-related images should be significant enough to divert attention away from any distracting and irrelevant images [28]. Evidence of the effect of embellishments and icons on perceptual complexity can be seen in the participants' comments. One participant with ADHD said the pictographs were "easier to process (P62, ADHD)", and another stated that charts with visual embellishments were "more engaging (P21, ADHD)." However, there is a balance, as one participant wrote, "Images are helpful and nice, but the little logos are too much and chaotic (P16, ADHD)." This study found a difference in the effectiveness of charts with visual embellishments and pictographs between tasks.

This study's search-based questions asked participants to identify and match values with target variables in the questions, and pictographs were the worst embellishment type for these questions. In data visualization, text acts to convey details and mathematical information, whereas visual elements better help viewers to understand the data set's shape [49]. For these questions, participants perform their searches mostly based on numerical values, and the added complexity of individual icons in pictographs distracted them from their task [29]. Additionally, for tasks that require searching for exact values, pictographs tend to cause viewers to count each individual item, dramatically increasing response time [15, 54]. This inclination to count can be seen in comments left by four participants with ADHD. One participant stated that they were not satisfied with how one icon did not equate to one count of the item (e.g., one cup image in the pictograph represented three drink orders). Another participant said, "[The pictograph] looks too busy and gives me the urge to count the icons to double check and waste my time confirming the statistics (P49, ADHD)." Although the study results found differences between response times across both groups when participants used plain bar charts and charts with visual embellishments, the difference between these embellishment types for the ADHD group was marginal. This may be because participants do not feel the need to count when they are provided with a single image. Since charts using visual embellishments did not significantly improve response times or accuracy of those with ADHD, this guideline recommends using regular plain bar charts for search-based questions.

The results saw a different trend for the ratio and min/max questions. Ratio questions asked participants to estimate the proportions of the categorical variables relative to the whole data set. None of the embellishment types significantly affected response times for the ratio questions; however, pictographs contributed to the highest accuracy overall. It was found that, when using pictographs, people turned to broad estimation tactics when asked to estimate ratios rather than attempting to count the icons [54]. Additionally, plain bar charts are useful for position and length estimation, not for area estimation [20]. These observations may be applied to people with ADHD for ratio questions. This may account for why pictographs perform better for these tasks than plain bar charts. In pictographs, more icons represented larger values, and fewer icons represented smaller values. Thus, it was easier to compare proportions in the ratio questions and to find the largest/smallest value in min/max questions. A possible explanation for why charts with visual embellishments did not improve responses as much despite also acting as a visual metaphor is that they did not aid value estimation in that way. The image's size or shape did not correlate with the value of the categorical variable, so it merely acted as a distractor [29].

One participant with ADHD commented, "I like the way [the pictograph] uses cups to symbolize an actual number. The bonus images in [the chart using visual embellishments] just make it more distracting (P8, ADHD)." This comment shows that this participant made a connection between the cups and the value of the variable, but that connection is not seen in the chart using visual embellishments. The images may have helped in min/max tasks more if they were placed at the top of the bar, since their heights would then be mapped to a value in the graph. The effect of placement and size of the visual embellishments needs to be further studied.

The use of icons appears to benefit viewers more than plain bar charts when the task requires more knowledge about the structure of the data, such as in ratio or min/max questions. Plain bar charts appear to benefit viewers more than charts using visual embellishments or icons in simple search-and-find tasks where only textual information, like numerical values, is needed. This leads this guideline on the use of visual embellishments or icons to be dependent on the chart's goal. Overall, however, those with ADHD did not perform very differently from those with ADHD when comparing embellishment types specifically.

Manage a gap between user preferences and chart performance: This study's findings suggested that hypothesis **H4** is **supported**. Designers should be cautious and deliberate when using more subjective measures, such as user preference, to influence chart design when creating accessible visualizations for audiences with ADHD. Across the entire study, the visualization preferences of participants with ADHD did not align with the charts that led to the best response times or accuracy. Other prior research has found this disconnect to be related to participants' preferences for graphs that are familiar [56]. When studying why people make certain color decisions for graphs, semantic associations, which depend on cultural context, and bias were found to affect reasoning [2]. Studies also found a relationship between dislike for a chart and how much time a participant perceives is needed to understand and respond to a chart, regardless of actual performance [15, 85].

A gap between user preferences and chart performance for people with ADHD may also be explained by the priming factors of hyperfocus. Hyperfocus has been found to be activated by both enjoyment [7] and by stress [32]. It is possible that for certain tasks in this survey, participants with ADHD were motivated by stress, which would lead to their high performance as well as their dislike of the charts. Although they enjoyed certain other chart components, they may not have been as motivated to answer the questions correctly while in a more relaxed state. Therefore, understanding the preferences of a viewer with ADHD may be important in increasing engagement with data visualizations and lead to hyperfocus status by enjoyment, not stress.

This study also showed that chart preference appears to be a subjective factor tied to the individual, not to ADHD symptoms. The study collected many contrasting comments on preferences between participants with ADHD. One participant with ADHD said, "The red chart seems to be more easily readable (P1, ADHD)", but another said, "Red is hard to read (P50, ADHD)." One participant called the Level 2 chart the "best visualization" despite choosing the Level 3 chart as their favorite because it "had the most information (P6, ADHD)." A split between preference and effectiveness of the chart can also be seen when one participant with ADHD commented, "[the pictograph] has too much going on, it's interesting but not intuitive (P40, ADHD)."

Charts with visual embellishments were cited as being helpful in reinforcing the text. One participant described the chart using visual embellishments as the "fastest to read (P20, ADHD)". Another participant with ADHD agreed that they were "more engaging as it contains visualization of [variable types]", whereas the pictographs were "unnecessarily complicated (P21, ADHD)". This was not reflected in the response times of this study. Many of the participants (eleven participants with ADHD) used the term "distracting" as a reason for why they did not like either the chart with visual embellishments or the pictograph. Some of the participants (nine participants with ADHD) said “less was more” and “simplicity is best.”

From these results, it appears that a study focus of just ADHD did yield different results from those of Wu et al. [85], which found participants with intellectual and developmental disabilities (IDD) showed a greater inclination towards icons as compared to those without IDD. In this study, fewer participants with ADHD preferred the pictographs over those without ADHD. This identifies a need to differentiate between ADHD and IDD in data visualization design. Designers aiming to create visualizations specifically made to address an audience of people with ADHD should carefully consider a balance between their stated preferences and the goals of the chart.

6.1 Limitations & Future Work

This work only covered a few chart components that can be adjusted to create more accessible visualizations – color, text amount, and types of additional embellishments. Future work may study the effect of blurring distracting chart features and animation on audiences with ADHD. These features have been studied before with the goal of improving educational tools for children who have ADHD [8]. For the color tasks, many other variables could be explored. This study focused on how hues affect response time and accuracy without varying the size of the markings. However, it has been shown that the size of the marking affects color perception in a general audience [78]. The interacting effect of chart marking sizes and colors on audiences with ADHD should be examined. Other color palettes outside of those belonging to ColorBrewer could also be examined for their accessibility. There is little research on the relationship between color and the interpretability of a line chart, especially with the added context of ADHD. Therefore, future studies should investigate whether colors used in the text amount task or the embellishment tasks may have had interacting effects with the results. Future research should also expand upon this survey to investigate how color, text amount, and embellishment type interact with ADHD in the context of other chart types and encoding choices. Similarly, future work may investigate how chart components interact with ADHD in the context of other task goals.

There are limitations to this study that could be later examined. In all three tasks, the similarity of accuracy and response time between the groups may be explained by the competitive and goal-oriented nature of the survey. This is something that is not always seen in real-world visualizations, such as when a viewer encounters a chart passively online. The effects of "hyperfocus" and the study of how and whether to activate such a state in those with ADHD should be considered in the context of data visualizations. This study used a crowd-sourcing service and an online survey, and in order to increase access to the survey, computers, phones, and tablets were all allowed as testing equipment. Thus, there was no guarantee that participants viewed the stimuli at the intended size. The brightness of the screens may also have been variable and have affected the color-identifying tasks. A controlled setting in a lab could be created now based on the results of this study. The use of eye-tracking software in order to better understand the preferences and responses could then also be used.

In addition, it should be acknowledged that since an online survey was used to collect responses, there was no control for when the participants took the survey. This is especially the case if respondents lived in several different time zones. This may have a slight interacting effect with the results since it was found that learning later in the day is especially improved for those with ADHD [72]. However, since the time at which a viewer interacts with a data visualization is not something that can be easily controlled in real-world situations, the effects of controlling the time of day at which experiments are conducted will need to be further contemplated.

Finally, ADHD medicine can help to manage but not to fully eliminate symptoms of ADHD. Medication usage was not considered in this study. The use of medication may have changed the performance parameters of each individual. Furthermore, the type and dosage of medication could also change a participant's performance, and the effects may be different for each person. This is something that could be considered in future studies.

Chapter 7

Conclusion

This work investigated how people with ADHD understand data visualizations, as compared to people without ADHD. A crowd-sourced survey was conducted to measure how different chart components affect the response times and accuracy of people with and without ADHD. The results lead to preliminary suggestions for how to create more equitable data visualization design decisions for adults with ADHD. This thesis discovered that color and text amount do not affect those with ADHD and those without ADHD differently, and that the effects of text amount and visual embellishments in graphs depend on the task associated with a chart. Across all the experiments, participants' preferences did not directly match how easy the chart was to process. This prompts further study on how personal design preferences combined with ADHD can limit the effectiveness of a chart. This work expands upon and verifies previous discoveries to broaden the frontier of accessibility in data visualizations by understanding the differences in visualization literacy between people with and without ADHD.

References

[1] ADDA. *ADHD Is Not a Learning Disability (But it Does Affect Learning)*. https://add.org/is-adhd-a-learning-disability/. 2023.

[2] J. Ahmad, E. Huynh, and F. Chevalier. "When Red Means Good, Bad, or Canada: Exploring People's Reasoning for Choosing Color Palettes". In: *2021 IEEE Visualization Conference (VIS)*. Oct. 2021, pp. 56–60. DOI: 10.1109/VIS49827.2021.9623314.

[3] D. Ahmetovic et al. "AudioFunctions.Web: Multimodal Exploration of Mathematical Function Graphs". In: *Proceedings of the 16th International Web for All Conference*. W4A '19. San Francisco, CA, USA: Association for Computing Machinery, 2019. ISBN: 9781450367165. DOI: 10.1145/3315002.3317560. URL: https://doi.org/10.1145/3315002.3317560.

[4] M. Z. I. Alam, S. Islam, and E. Hoque. "SeeChart: Enabling Accessible Visualizations Through Interactive Natural Language Interface For People with Visual Impairments". In: *Proceedings of the 28th International Conference on Intelligent User Interfaces*. IUI '23. Sydney, NSW, Australia: Association for Computing Machinery, 2023, pp. 46–64. ISBN: 9798400701061. DOI: 10.1145/3581641.3584099. URL: https://doi.org/10.1145/3581641.3584099.

[5] Y. Alqahtani et al. "Understanding How ADHD Affects Visual Information Processing". In: *Universal Access in Human-Computer Interaction. Multimodality and Assistive Environments*. Ed. by M. Antona and C. Stephanidis. Cham: Springer International Publishing, 2019, pp. 23–31. ISBN: 978-3-030-23563-5.

[6] American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders*. en. Fifth Edition. American Psychiatric Association, May 2013. ISBN: 978-0-89042-555-8 978-0-89042-557-2. DOI: 10.1176/appi.books.9780890425596. URL: https:

//psychiatryonline.org/doi/book/10.1176/appi.books.9780890425596 (visited on 07/13/2023).

[7] B. K. Ashinoff and A. Abu-Akel. "Hyperfocus: the forgotten frontier of attention". en. In: *Psychological Research* 85.1 (Feb. 2021), pp. 1–19. ISSN: 0340-0727, 1430-2772. DOI: 10.1007/s00426-019-01245-8. URL: http://link.springer.com/10.1007/s00426-019-01245-8 (visited on 08/07/2023).

[8] O. Asiry et al. "Extending Attention Span for Children ADHD Using an Attentive Visual Interface". In: *2018 22nd International Conference Information Visualisation (IV)*. Fisciano, Italy: IEEE, July 2018, pp. 188–193. ISBN: 978-1-5386-7202-0. DOI: 10.1109/iV.2018.00041. URL: https://ieeexplore.ieee.org/document/8564159/ (visited on 08/07/2023).

[9] A. Bellato et al. "Association between ADHD and vision problems. A systematic review and meta-analysis". eng. In: *Molecular Psychiatry* 28.1 (Jan. 2023), pp. 410–422. ISSN: 1476-5578. DOI: 10.1038/s41380-022-01699-0.

[10] N. Boot, B. Nevicka, and M. Baas. "Creativity in ADHD: Goal-Directed Motivation and Domain Specificity". en. In: *Journal of Attention Disorders* 24.13 (Nov. 2020), pp. 1857–1866. ISSN: 1087-0547, 1557-1246. DOI: 10.1177/1087054717727352. URL: http://journals.sagepub.com/doi/10.1177/1087054717727352 (visited on 08/07/2023).

[11] R. Borgo et al. "An Empirical Study on Using Visual Embellishments in Visualization". In: *IEEE Transactions on Visualization and Computer Graphics* 18.12 (Dec. 2012). Conference Name: IEEE Transactions on Visualization and Computer Graphics, pp. 2759–2768. ISSN: 1941-0506. DOI: 10.1109/TVCG.2012.197.

[12] M. A. Borkin et al. "What Makes a Visualization Memorable?" In: *IEEE Transactions on Visualization and Computer Graphics* 19.12 (Dec. 2013), pp. 2306–2315. ISSN: 1077-2626. DOI: 10.1109/TVCG.2013.234. URL: http://ieeexplore.ieee.org/document/6634103/ (visited on 07/16/2023).

[13] C. Brewer. *Color use guidelines for mapping and visualization. Visualization in Modern Cartography*. 1994.

[14] R. Bujack et al. “The Good, the Bad, and the Ugly: A Theoretical Framework for the Assessment of Continuous Colormaps”. In: *IEEE Transactions on Visualization and Computer Graphics* 24.1 (2018), pp. 923–933. DOI: 10.1109/TVCG.2017.2743978.

[15] A. Burns et al. “Designing With Pictographs: Envision Topics Without Sacrificing Understanding”. In: *IEEE Transactions on Visualization and Computer Graphics* 28.12 (Dec. 2022), pp. 4515–4530. ISSN: 1077-2626, 1941-0506, 2160-9306. DOI: 10.1109/TVCG.2021.3092680. URL: https://ieeexplore.ieee.org/document/9465643/ (visited on 07/15/2023).

[16] CDC. *Symptoms and Diagnosis of ADHD*. https://www.cdc.gov/ncbddd/adhd/diagnosis.html. 2022.

[17] CDC. *What is ADHD?* https://www.cdc.gov/ncbddd/adhd/facts.html. 2022.

[18] A. Chaparro and M. Chaparro. “Applications of Color in Design for Color-Deficient Users”. In: *Ergonomics in Design* 25.1 (2017), pp. 23–30. DOI: 10.1177/1064804616635382. eprint: https://doi.org/10.1177/1064804616635382. URL: https://doi.org/10.1177/1064804616635382.

[19] N. W. Cherukuru et al. “Beyond Visuals : Examining the Experiences of Geoscience Professionals With Vision Disabilities in Accessing Data Visualizations”. In: (2022). Publisher: arXiv Version Number: 1. DOI: 10.48550/ARXIV.2207.13220. URL: https://arxiv.org/abs/2207.13220 (visited on 07/12/2023).

[20] W. S. Cleveland and R. McGill. “Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods”. In: *Journal of the American Statistical Association* 79.387 (1984), pp. 531–554. DOI: 10.1080/01621459.1984.10478080. eprint: https://www.tandfonline.com/doi/pdf/10.1080/01621459.1984.10478080. URL: https://www.tandfonline.com/doi/abs/10.1080/01621459.1984.10478080.

[21] R. Coelho, P. Mattos, and R. Tannock. “Attention-Deficit Hyperactivity Disorder (ADHD) and narrative discourse in older adults”. In: *Dementia & Neuropsychologia* 12.4 (Dec. 2018), pp. 374–379. ISSN: 1980-5764, 1980-5764. DOI: 10.1590/1980-

57642018dn12-040006. URL: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1980-57642018000400374&lng=en&tlng=en (visited on 09/10/2023).

[22] Cynthia Brewer, Mark Harrower and The Pennsylvania State University. *ColorBrewer: Color Advide for Maps)*. https://colorbrewer2.org/. 2023.

[23] B. S. Da Silva et al. "An overview on neurobiology and therapeutics of attention-deficit/hyperactivity disorder". en. In: *Discover Mental Health* 3.1 (Jan. 2023), p. 2. ISSN: 2731-4383. DOI: 10.1007/s44192-022-00030-1. URL: https://link.springer.com/10.1007/s44192-022-00030-1 (visited on 07/13/2023).

[24] J. D. Daron et al. "Interpreting climate data visualisations to inform adaptation decisions". In: *Climate Risk Management* 10 (2015), pp. 17–26. ISSN: 2212-0963. DOI: https://doi.org/10.1016/j.crm.2015.06.007. URL: https://www.sciencedirect.com/science/article/pii/S221209631500025X.

[25] F. Elavsky, C. Bennett, and D. Moritz. "How accessible is my visualization? Evaluating visualization accessibility with Chartability". en. In: *Computer Graphics Forum* 41.3 (June 2022), pp. 57–70. ISSN: 0167-7055, 1467-8659. DOI: 10.1111/cgf.14522. URL: https://onlinelibrary.wiley.com/doi/10.1111/cgf.14522 (visited on 11/29/2022).

[26] C. Engel, E. F. Müller, and G. Weber. "SVGPlott: An Accessible Tool to Generate Highly Adaptable, Accessible Audio-Tactile Charts for and from Blind and Visually Impaired People". In: *Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments*. PETRA '19. Rhodes, Greece: Association for Computing Machinery, 2019, pp. 186–195. ISBN: 9781450362320. DOI: 10.1145/3316782.3316793. URL: https://doi.org/10.1145/3316782.3316793.

[27] D. Fan et al. "The Accessibility of Data Visualizations on the Web for Screen Reader Users: Practices and Experiences During COVID-19". In: *ACM Trans. Access. Comput.* 16.1 (Mar. 2023). ISSN: 1936-7228. DOI: 10.1145/3557899. URL: https://doi.org/10.1145/3557899.

[28] S. Forster and N. Lavie. "Establishing the Attention-Distractibility Trait". en. In: *Psychological Science* 27.2 (Feb. 2016), pp. 203–212. ISSN: 0956-7976, 1467-9280. DOI:

10.1177/0956797615617761. URL: http://journals.sagepub.com/doi/10.1177/0956797615617761 (visited on 07/17/2023).

[29] S. Forster et al. "Plugging the attention deficit: Perceptual load counters increased distraction in ADHD." en. In: *Neuropsychology* 28.1 (Jan. 2014), pp. 91–97. ISSN: 1931-1559, 0894-4105. DOI: 10.1037/neu0000020. URL: http://doi.apa.org/getdoi.cfm?doi=10.1037/neu0000020 (visited on 07/17/2023).

[30] L. A. Friedman and J. L. Rapoport. "Brain development in ADHD". en. In: *Current Opinion in Neurobiology* 30 (Feb. 2015), pp. 106–111. ISSN: 09594388. DOI: 10.1016/j.conb.2014.11.007. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959438814002335 (visited on 09/14/2023).

[31] D. J. Gillan and E. H. Richman. "Minimalism and the Syntax of Graphs". In: *Human Factors* 36.4 (1994), pp. 619–644. DOI: 10.1177/001872089403600405. eprint: https://doi.org/10.1177/001872089403600405. URL: https://doi.org/10.1177/001872089403600405.

[32] Y. Groen et al. "Testing the relation between ADHD and hyperfocus experiences". In: *Research in Developmental Disabilities* 107 (2020), p. 103789. ISSN: 0891-4222. DOI: https://doi.org/10.1016/j.ridd.2020.103789. URL: https://www.sciencedirect.com/science/article/pii/S0891422220302213.

[33] R. J. Gropper and R. Tannock. "A Pilot Study of Working Memory and Academic Achievement in College Students With ADHD". In: *Journal of Attention Disorders* 12.6 (2009). PMID: 19380519, pp. 574–581. DOI: 10.1177/1087054708320390. eprint: https://doi.org/10.1177/1087054708320390. URL: https://doi.org/10.1177/1087054708320390.

[34] S. Haroz, R. Kosara, and S. L. Franconeri. "ISOTYPE Visualization: Working Memory, Performance, and Engagement with Pictographs". en. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. Seoul Republic of Korea: ACM, Apr. 2015, pp. 1191–1200. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702275. URL: https://dl.acm.org/doi/10.1145/2702123.2702275 (visited on 11/14/2023).

[35] M. Harrower and C. A. Brewer. "ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps". en. In: *The Cartographic Journal* 40.1 (June 2003), pp. 27–37. ISSN: 0008-7041, 1743-2774. DOI: 10.1179/000870403235002042. URL: http://www.tandfonline.com/doi/full/10.1179/000870403235002042 (visited on 08/30/2023).

[36] M. Hearst and M. Tory. "Would You Like A Chart With That? Incorporating Visualizations into Conversational Interfaces". In: *2019 IEEE Visualization Conference (VIS)*. Institute of Electrical and Electronics Engineers, 2019, pp. 1–5. DOI: 10.1109/VISUAL.2019.8933766.

[37] J. Holsanova, N. Holmberg, and K. Holmqvist. "Tracing integration of text and pictures in newspaper reading". In: *Lund University Cognitive Studies* 125 (2005), pp. 1–19.

[38] C. Huang. "A Snapshot Into ADHD: The Impact of Hyperfixations and Hyperfocus From Adolescence to Adulthood". In: *Journal of Student Research* 11.3 (Aug. 2022). ISSN: 2167-1907. DOI: 10.47611/jsrhs.v11i3.2987. URL: https://jsr.org/hs/index.php/path/article/view/2987 (visited on 09/09/2023).

[39] K. E. Hupfeld, T. R. Abagis, and P. Shah. "Living "in the zone": hyperfocus in adult ADHD". en. In: *ADHD Attention Deficit and Hyperactivity Disorders* 11.2 (June 2019), pp. 191–208. ISSN: 1866-6116, 1866-6647. DOI: 10.1007/s12402-018-0272-y. URL: http://link.springer.com/10.1007/s12402-018-0272-y (visited on 08/07/2023).

[40] W. Javed, B. McDonnel, and N. Elmqvist. "Graphical Perception of Multiple Time Series". In: *IEEE Transactions on Visualization and Computer Graphics* 16.6 (2010), pp. 927–934. DOI: 10.1109/TVCG.2010.162.

[41] D. H. Kim, V. Setlur, and M. Agrawala. "Towards Understanding How Readers Integrate Charts and Captions: A Case Study with Line Charts". In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI '21. Yokohama, Japan: Association for Computing Machinery, 2021. ISBN: 9781450380966. DOI: 10.1145/3411764.3445443. URL: https://doi.org/10.1145/3411764.3445443.

[42] J. Kim et al. "Exploring Chart Question Answering for Blind and Low Vision Users". In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. CHI '23. Hamburg, Germany: Association for Computing Machinery, 2023. ISBN:

9781450394215. DOI: 10.1145/3544548.3581532. URL: https://doi.org/10.1145/3544548.3581532.

[43] N. W. Kim et al. "Accessible Visualization: Design Space, Opportunities, and Challenges". en. In: *Computer Graphics Forum* 40.3 (2021). _eprint: https://onlinelibrary.wiley.com/doi/p pp. 173–188. ISSN: 1467-8659. DOI: 10.1111/cgf.14298. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.14298 (visited on 07/12/2023).

[44] S. Kim, S. Chen, and R. Tannock. "Visual function and color vision in adults with Attention-Deficit/Hyperactivity Disorder". en. In: *Journal of Optometry* 7.1 (Jan. 2014), pp. 22–36. ISSN: 18884296. DOI: 10.1016/j.optom.2013.07.001. URL: https://linkinghub.elsevier.com/retrieve/pii/S1888429613000538 (visited on 08/30/2023).

[45] S. Kim et al. "Color vision in ADHD: Part 2 - Does Attention influence Color Perception?" In: *Behavioral and Brain Functions* 10.1 (Oct. 2014), p. 39. ISSN: 1744-9081. DOI: 10.1186/1744-9081-10-39. URL: https://doi.org/10.1186/1744-9081-10-39 (visited on 11/29/2022).

[46] S. Kim et al. "Colour vision in ADHD: Part 1 - Testing the retinal dopaminergic hypothesis". In: *Behavioral and Brain Functions* 10.1 (Oct. 2014), p. 38. ISSN: 1744-9081. DOI: 10.1186/1744-9081-10-38. URL: https://doi.org/10.1186/1744-9081-10-38 (visited on 11/29/2022).

[47] H.-K. Kong, Z. Liu, and K. Karahalios. "Frames and Slants in Titles of Visualizations on Controversial Topics". In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3174012. URL: https://doi.org/10.1145/3173574.3174012.

[48] H.-K. Kong, Z. Liu, and K. Karahalios. "Trust and Recall of Information across Varying Degrees of Title-Visualization Misalignment". In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: Association for Computing Machinery, 2019, pp. 1–13. ISBN: 9781450359702. DOI: 10.1145/3290605.3300576. URL: https://doi.org/10.1145/3290605.3300576.

[49] J. Koponen and J. Hildén. *Data visualization handbook*. eng. first edition. Aalto University publication series C 1/2019. Finland: Otavan kirjapaino, 2019. ISBN: 978-952-60-7449-8.

[50] L. M. Korenman and Z. F. Peynircioglu. “Individual Differences in Learning and Remembering Music: Auditory versus Visual Presentation”. In: *Journal of Research in Music Education* 55.1 (2007), pp. 48–64. DOI: 10.1177/002242940705500105. eprint: https://doi.org/10.1177/002242940705500105. URL: https://doi.org/10.1177/002242940705500105.

[51] G. La Malfa et al. “Detecting attention-deficit/hyperactivity disorder (ADHD) in adults with intellectual disability The use of Conners’ Adult ADHD Rating Scales (CAARS)”. In: *Res Dev Disabil* 29.2 (2008), pp. 158–64. ISSN: 0891-4222 (Print) 0891-4222. DOI: 10.1016/j.ridd.2007.02.002.

[52] M. Laasonen et al. “Project DyAdd: Phonological Processing, Reading, Spelling, and Arithmetic in Adults With Dyslexia or ADHD”. en. In: *Journal of Learning Disabilities* 43.1 (Jan. 2010), pp. 3–14. ISSN: 0022-2194, 1538-4780. DOI: 10.1177/0022219409335216. URL: http://journals.sagepub.com/doi/10.1177/0022219409335216 (visited on 07/10/2023).

[53] J. Lagacé-Leblanc, L. Massé, and N. Rousseau. “Academic Impairments Faced by College Students with Attention-Deficit Hyperactivity Disorder: A Qualitative Study”. en. In: *Journal of Postsecondary Education and Disability* 35.2 (2022). Publisher: Association on Higher Education and Disability ERIC Number: EJ1364189, pp. 131–144. ISSN: 2379-7762. URL: https://eric.ed.gov/?id=EJ1364189 (visited on 07/10/2023).

[54] Y. Lin et al. “A Perception Study for Unit Charts in the Context of Large-Magnitude Data Representation”. en. In: *Symmetry* 15.1 (Jan. 2023), p. 219. ISSN: 2073-8994. DOI: 10.3390/sym15010219. URL: https://www.mdpi.com/2073-8994/15/1/219 (visited on 09/05/2023).

[55] S. Lorenz et al. “Tailoring the visual communication of climate projections for local adaptation practitioners in Germany and the UK”. In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 373.2055 (2015),

p. 20140457. DOI: 10.1098/rsta.2014.0457. eprint: https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2014.0457. URL: https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2014.0457.

[56] S. Lorenz et al. "Tailoring the visual communication of climate projections for local adaptation practitioners in Germany and the UK". en. In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 373.2055 (Nov. 2015), p. 20140457. ISSN: 1364-503X, 1471-2962. DOI: 10.1098/rsta.2014.0457. URL: https://royalsocietypublishing.org/doi/10.1098/rsta.2014.0457 (visited on 09/05/2023).

[57] K. Lu et al. "Palettailor: Discriminable Colorization for Categorical Data". In: *IEEE Transactions on Visualization and Computer Graphics* 27.2 (2021), pp. 475–484. DOI: 10.1109/TVCG.2020.3030406.

[58] A. Marije Boonstra et al. "Executive functioning in adult ADHD: a meta-analytic review". en. In: *Psychological Medicine* 35.8 (Aug. 2005), pp. 1097–1108. ISSN: 0033-2917, 1469-8978. DOI: 10.1017/S003329170500499X. URL: https://www.cambridge.org/core/product/identifier/S003329170500499X/type/journal_article (visited on 09/04/2023).

[59] K. J. McCaffery et al. "The influence of graphic display format on the interpretations of quantitative risk information among adults with lower education and literacy: a randomized experimental study". In: *Med Decis Making* 32.4 (2012), pp. 532–44. ISSN: 0272-989x. DOI: 10.1177/0272989x11424926.

[60] A. C. Miller et al. "Reading comprehension in children with ADHD: Cognitive underpinnings of the centrality deficit". In: *Journal of abnormal child psychology* 41 (2013), pp. 473–483.

[61] A. Miranda et al. "Reading Performance of Young Adults With ADHD Diagnosed in Childhood: Relations With Executive Functioning". en. In: *Journal of Attention Disorders* 21.4 (Feb. 2017), pp. 294–304. ISSN: 1087-0547, 1557-1246. DOI: 10.1177/1087054713507977. URL: http://journals.sagepub.com/doi/10.1177/1087054713507977 (visited on 07/10/2023).

[62] A. Mohammed et al. “An Approach Towards Vision Correction Display and Color blindness”. In: *2022 2nd International Mobile, Intelligent, and Ubiquitous Computing Conference (MIUCC)*. Cairo, Egypt: IEEE, May 2022, pp. 153–159. ISBN: 978-1-66546-677-6. DOI: 10.1109/MIUCC55081.2022.9781710. URL: https://ieeexplore.ieee.org/document/9781710/ (visited on 07/24/2023).

[63] K. Mukherjee et al. “Context Matters: A Theory of Semantic Discriminability for Perceptual Encoding Systems”. In: (2021). Publisher: arXiv Version Number: 3. DOI: 10.48550/ARXIV.2108.03685. URL: https://arxiv.org/abs/2108.03685 (visited on 08/22/2023).

[64] P. Parsons and P. Shukla. “Data Visualization Practitioners’ Perspectives on Chartjunk”. In: *2020 IEEE Visualization Conference (VIS)*. Institute of Electrical and Electronics Engineers, 2020, pp. 211–215. DOI: 10.1109/VIS47514.2020.00049.

[65] S. Poret, R. D. Dony, and S. Gregori. “Image processing for colour blindness correction”. In: *2009 IEEE Toronto International Conference Science and Technology for Humanity (TIC-STH)*. Toronto, ON, Canada: IEEE, Sept. 2009, pp. 539–544. ISBN: 978-1-4244-3877-8. DOI: 10.1109/TIC-STH.2009.5444442. URL: http://ieeexplore.ieee.org/document/5444442/ (visited on 07/24/2023).

[66] Prolific. *Prolific)*. https://www.prolific.co/. 2023.

[67] B. Saket, A. Endert, and C. Demiralp. “Task-Based Effectiveness of Basic Visualizations”. In: *IEEE Transactions on Visualization and Computer Graphics* 25.7 (July 2019), pp. 2505–2512. ISSN: 1077-2626, 1941-0506, 2160-9306. DOI: 10.1109/TVCG.2018.2829750. URL: https://ieeexplore.ieee.org/document/8354901/ (visited on 08/29/2023).

[68] J. Schiewe. “Empirical Studies on the Visual Perception of Spatial Patterns in Choropleth MapsEmpirische Untersuchungen zur visuellen Wahrnehmung räumlicher Muster in Choroplethenkarten”. In: *KN - Journal of Cartography and Geographic Information* 69 (Aug. 2019). DOI: 10.1007/s42489-019-00026-y.

[69] K. B. Schloss et al. “Mapping Color to Meaning in Colormap Data Visualizations”. In: *IEEE Transactions on Visualization and Computer Graphics* 25.1 (Jan. 2019). Conference Name: IEEE Transactions on Visualization and Computer Graphics, pp. 810–819. ISSN: 1941-0506. DOI: 10.1109/TVCG.2018.2865147.

[70] A. Sharif et al. “VoxLens: Making Online Data Visualizations Accessible with an Interactive JavaScript Plug-In”. In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI ’22. New Orleans, LA, USA: Association for Computing Machinery, 2022. ISBN: 9781450391573. DOI: 10.1145/3491102.3517431. URL: https://doi.org/10.1145/3491102.3517431.

[71] S. C. Sibrel et al. “The relation between color and spatial structure for interpreting colormap data visualizations”. In: *Journal of Vision* 20.12 (Nov. 2020), p. 7. ISSN: 1534-7362. DOI: 10.1167/jov.20.12.7. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7683863/ (visited on 01/09/2023).

[72] M. Sindiani, M. Korman, and A. Karni. “Time-of-day matters in text learning and recall: Evening lessons are advantageous for adults with ADHD though not for typical peers”. en. In: *Learning and Instruction* 80 (Aug. 2022), p. 101630. ISSN: 09594752. DOI: 10.1016/j.learninstruc.2022.101630. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959475222000512 (visited on 07/05/2023).

[73] P. Song et al. “The prevalence of adult attention-deficit hyperactivity disorder: A global systematic review and meta-analysis”. In: *Journal of global health* 11 (2021).

[74] L. South and M. Borkin. *Generating Seizure-Inducing Sequences with Interactive Visualizations*. preprint. Open Science Framework, Oct. 2020. DOI: 10.31219/osf.io/85gwy. URL: https://osf.io/85gwy (visited on 07/24/2023).

[75] L. South and M. A. Borkin. “Photosensitive Accessibility for Interactive Data Visualizations”. In: *IEEE Transactions on Visualization and Computer Graphics* 29.1 (Jan. 2023). Conference Name: IEEE Transactions on Visualization and Computer Graphics, pp. 374–384. ISSN: 1941-0506. DOI: 10.1109/TVCG.2022.3209359.

[76] L. South, D. Saffo, and M. Borkin. *Detecting and Defending Against Seizure-Inducing GIFs in Social Media.* preprint. Open Science Framework, Jan. 2021. DOI: 10.31219/osf.io/4kgu6. URL: https://osf.io/4kgu6 (visited on 07/24/2023).

[77] C. Stokes et al. “Striking a Balance: Reader Takeaways and Preferences when Integrating Text and Charts”. In: *IEEE Transactions on Visualization and Computer Graphics* (2022). arXiv:2208.01780 [cs], pp. 1–11. ISSN: 1077-2626, 1941-0506, 2160-9306. DOI: 10.1109/TVCG.2022.3209383. URL: http://arxiv.org/abs/2208.01780 (visited on 11/29/2022).

[78] D. A. Szafir. “Modeling Color Difference for Visualization Design”. en. In: *IEEE Transactions on Visualization and Computer Graphics* 24.1 (Jan. 2018), pp. 392–401. ISSN: 1077-2626. DOI: 10.1109/TVCG.2017.2744359. URL: http://ieeexplore.ieee.org/document/8017604/ (visited on 05/10/2023).

[79] Tomoyuki Ohkubo and Kazuyuki Kobayashi. “A color compensation vision system for color-blind people”. In: *2008 SICE Annual Conference.* Chofu: IEEE, Aug. 2008, pp. 1286–1289. ISBN: 978-4-907764-30-2. DOI: 10.1109/SICE.2008.4654855. URL: http://ieeexplore.ieee.org/document/4654855/ (visited on 07/24/2023).

[80] G. Tripp and J. R. Wickens. “Neurobiology of ADHD”. en. In: *Neuropharmacology* 57.7-8 (Dec. 2009), pp. 579–589. ISSN: 00283908. DOI: 10.1016/j.neuropharm.2009.07.026. URL: https://linkinghub.elsevier.com/retrieve/pii/S0028390809002445 (visited on 07/10/2023).

[81] E. R. Tufte. *The Visual Display of Quantitative Information.* 2nd ed. Cheshire, CT: Graphics Press, 2001.

[82] C. Ware. “Color sequences for univariate maps: theory, experiments and principles”. In: *IEEE Computer Graphics and Applications* 8.5 (Sept. 1988), pp. 41–49. ISSN: 0272-1716. DOI: 10.1109/38.7760. URL: http://ieeexplore.ieee.org/document/7760/ (visited on 09/10/2023).

[83] M. L. Waskom. “seaborn: statistical data visualization”. In: *Journal of Open Source Software* 6.60 (2021), p. 3021. DOI: 10.21105/joss.03021. URL: https://doi.org/10.21105/joss.03021.

[84] K. Wu et al. “Data, Data, Everywhere: Uncovering Everyday Data Experiences for People with Intellectual and Developmental Disabilities”. en. In: *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. Hamburg Germany: ACM, Apr. 2023, pp. 1–17. ISBN: 978-1-4503-9421-5. DOI: 10.1145/3544548.3581204. URL: https://dl.acm.org/doi/10.1145/3544548.3581204 (visited on 07/23/2023).

[85] K. Wu et al. “Understanding Data Accessibility for People with Intellectual and Developmental Disabilities”. en. In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Yokohama Japan: ACM, May 2021, pp. 1–16. ISBN: 978-1-4503-8096-6. DOI: 10.1145/3411764.3445743. URL: https://dl.acm.org/doi/10.1145/3411764.3445743 (visited on 07/24/2023).

[86] L. Zhou and C. D. Hansen. “A Survey of Colormaps in Visualization”. In: *IEEE Transactions on Visualization and Computer Graphics* 22.8 (Aug. 2016), pp. 2051–2069. ISSN: 1077-2626. DOI: 10.1109/TVCG.2015.2489649. URL: http://ieeexplore.ieee.org/document/7305807/ (visited on 09/08/2023).

[87] P. Zieliński. “An arousal effect of colors saturation: A study of self-reported ratings and electrodermal responses”. In: *Journal of Psychophysiology* 30 (2016). Place: Germany Publisher: Hogrefe Publishing, pp. 9–16. ISSN: 2151-2124. DOI: 10.1027/0269-8803/a000149.

Appendix A

Participants' Demographics Information

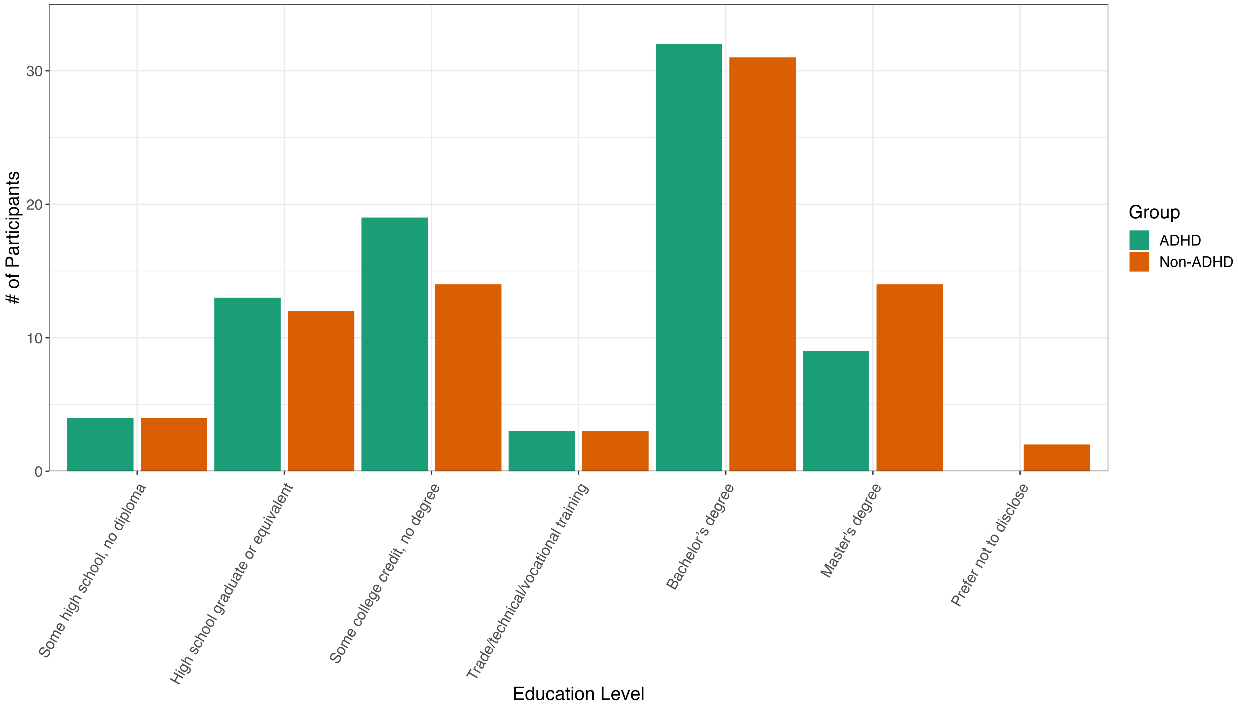


Figure A.1: A histogram showing the breakdown of education levels for the participants with ADHD and those without ADHD. The two groups have shown similar distributions. In this figure, we do not show education levels that were in the survey options but not selected by any of the participants (e.g., No schooling completed, Associate degree, and Doctorate degree).