AN ANALYSIS OF OPERATOR EYE BEHAVIOR WHEN MONITORING SIMULATED, PETROCHEMICAL MANUFACTURING, SUPERVISORY CONTROL AND DATA ACQUISITION ALERTS AND WARNINGS WITH BACKGROUND NOISE

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ABSTRACT

There are a number of potential distractions for operators when viewing plant status-monitoring information in a petrochemical plant: background noises of other employees speaking, sounds of manufacturing equipment and processes and other ambient noises like HVAC and building operation noise. When the monitoring equipment for a chemical or petrochemical plant is not designed to take into account that operators can be distracted by this noise, there is a potential safety hazard for the people in that work environment. Alarms can be missed and fundamental information can be overlooked.

SCADA is "a type of control system that collects and displays data and allows users to manipulate and control the system from a distant location (Koffskey, 2010)." SCADA is used in various industries such as energy, food and beverage, manufacturing, oil and gas, power, recycling, transportation, and water and waste water (Gould, 2017). In the petrochemical industry, the status of individual instruments is monitored by one or a few supervisors at a central command station with a SCADA screen.

The focus of this research is to determine if there is a difference in user eye behavior (Time to First Fixation, Fixation Frequency per AOI, Gaze Duration Mean, and Gaze Percentage per AOI) between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface? 100 participants (with a science, engineering, or manufacturing background) were asked to watch two sets of simulated SCADA prototypes (half with petrochemical manufacturing noise and half without) while wearing a set of eye-tracking glasses. The Wilconox Rank Sum Test determined that there was a statistically significant difference in the data sets (with three of the four dependent variables) demonstrating that sound is statistically significant in distracting operators watching a petrochemical SCADA user interface.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Need for the Study

In March of 1979, the Three Mile Island nuclear power plant's reaction core overheated, because of an issue with the main monitoring system's alerting features. The operators had no idea there was an issue until it was too late to mitigate the issue. The indicator panel displayed an alarm to operators, but the alarm wasn't readily apparent and operators were distracted by other activity in the control room while they were monitoring the overall status of the plant (United States Nuclear Regulatory Commission, 2013).

There are a lot of distractions at a chemical and petrochemical plant for operators: background noises of other employees speaking, sounds of manufacturing equipment and processes and other ambient noises like HVAC and building operation noise. When the monitoring equipment for a chemical or petrochemical plant is not designed to take into account that operators can be distracted by this noise, there is a potential safety hazard for the people in that work environment. Alarms can be missed and fundamental information can be overlooked. Qadri (2017) notes the following:

> Good user experiences don't happen by chance. They are purposely designed through a user experience design process that aims to create a solution that meets both business and user needs, resulting in systems that are intuitive, useful, and pleasant to use. This is also

true when it comes to Human Machine Interface (HMI)/SCADA systems.

The usability of a user interface is not just important for commercial goods, but it is also fundamental for the screens in industry as well. Besides safety concerns, the effectiveness, efficiency and productivity of the industry may be negatively affected if the operators are having trouble using the equipment due to poorly-designed interfaces (Qadri, 2017). This issue can ultimately lead to a loss of profits for a company too if these issues are not resolved in a timely manner.

Merriam Webster (2003) defines noise as “any sound that is undesired or interferes with one's hearing of something.” Cassidy, Raymond and MacDonald (2007) noted that the presence of music and background noise with high arousal potential negatively affected the cognitive performance of participants when completing tasks. They found that overall the performance of the users to perform tasks was lower when there was background sound (noise or music) as compared to that of silence (Cassidy, Raymond and MacDonald). While there has been a link in the literature to noise being a distraction to users, there hasn’t been a correlation of noise and how it affects the eye behavior of operators.

Significance and Purpose of the Study

Subnet Solutions (2017) defines SCADA as “an acronym for Supervisory Control and Data Acquisition. SCADA generally refers to an industrial computer system that monitors and controls a process (Subnet Solutions, 2017).” SCADA allows for the monitoring of an entire petrochemical plant from one location, and all the inputs and outputs are displayed graphically on the SCADA system. The screen also gives real time information about set points and alarm information. This study identified the type of information that the user tended to focus their attention on when monitoring a SCADA display. This study provided insight into the mental model of the operator when ambient noise was present and how it affects their ability to respond to alerts and warnings.

Statement of the Problem

Is there a difference in user eye behavior (Time to First Fixation, Fixation Frequency per AOI, Gaze Duration Mean, and Gaze Percentage per AOI) between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface?

Definition of Terms

<u>Area or Interest (AOI)</u>: This is an area or portion of a user interface or localized viewing area that is defined by the research team (Jacobs & Karn, 2002).

<u>Eye Tracking</u>: Eye tracking is a standard usability study tool to capture eye gaze and identify the mental model of a user viewing information or performing tasks on a user interface (Yarbus, 1967).

<u>Fixation Frequency per AOI</u>: This is the total count of fixation counts (number of times participant's eye entered the AOI from the background area of the screen) divided by the AOI visible time (time that the AOI was actively collecting statistics) (Koffskey, 2010).

<u>Fixation or Gaze Duration</u>: The gaze or fixation duration is generally described with respect to an AOI; it is the total duration of time the eye has spent viewing an AOI for a particular study (Jacobs & Karn, 2002).

<u>Fixation or Gaze Point</u>: A fixation or gaze point occurs when the eye slows or stops on a particular spot for a period of time (Jacobs & Karn, 2002).

<u>Gaze Duration Mean</u>: This is the dwell time divided by the fixation count (Koffskey, 2010).

Dwell Time: This "starts at the moment the AOI is fixated and ends at the moment the last fixation on the AOI ends = the sum of durations from all fixations and saccades that hit the AOI" (SensoMotoric Instruments, 2011a).

Gaze Percentage per AOI: This is the overall total dwell time for a particular AOI divided by the total time of the study (Koffskey, 2010).

Gaze Plots: These are visualizations of how the participant viewed an area; they show the fixation locations and durations, saccades and the overall scan path for a user (Tobii, 2017).

Hard Points: Hard points are those that are visual representations of ether an input or output connected to the system (Dumitru & Gligor, 2012).

Heat Map: These show the visual attenuated focus for several hundred participants all at once (Tobii, 2017).

Points: "SCADA systems typically implement a distributed database, commonly referred to as a tag database, which contains data elements called tags or points. A point represents a single input or output value monitored or controlled by the system (Kim, 2010)."

Saccade: When the eye travels between fixations or gaze points, this eye movement is called a saccade (iMotions, 2015).

SCADA: "An acronym for Supervisory Control and Data Acquisition. SCADA generally refers to an industrial computer system that monitors and controls a process (Subnet Solutions, 2017)."

Scan Path: This is "a spatial arrangement of a sequence of fixations (Jacobs & Karns, 2002)."

Soft Points: Soft points are screen representations that demonstrate a logic or math operation (Dumitru & Gligor, 2012).

Assumptions

1. The SCADA screens created for this study were representative of a petrochemical

manufacturing plant.

2. The operators chosen for the study were representative of the user population for a SCADA user interface.
3. The workload for the user interface was medium – meaning an average number of point value changes and alarms.
4. The sound recording was representative of a petrochemical manufacturing plant (including background noise and manufacturing machine and processing noises).
5. The presence of external factors (i.e. visual lighting levels and olfactory conditions) affecting the results of the study were reduced by holding the study in the same conference room at the same time of day for all participants.

Limitations

1. The study was limited to the petrochemical industry and display inputs and outputs that were generally represented on a screen for that industry.
2. The study was limited to a user sample population in the New Jersey, New York and Pennsylvania area due to equipment travel limitations.
3. The study was performed with a simulated SCADA prototype based on examples from websites such as Reliance.SCADA.com, Tyconautomation.com, Nishcon.com, Wonderware.com or Fultek.com.
4. The study was performed from 12pm to 2pm each day due to limited lunchtime availability of participants.

Delimitations

1. Participants had a science, engineering, or manufacturing background (work experience or technical training in one of these three fields). The participants were expected to have a basic understanding of the information being displayed on the SCADA prototype used in the study.

Summary of Testing

A hypothetical scenario or use case was read to the participants to provide background before the users were exposed to the user interface. The participants were then asked to take a seat at a workstation that displays the SCADA prototype, and they put on the wearable eye tracking glasses. After a short calibration sequence, the eye tracking session began and was recorded using the Tobii Pro controlling software. For scenario A, the user was given five minutes to view the SCADA dynamic interface. The point values changed and alarms triggered as they would in a normal petrochemical plant with a medium level workload.

At the end of the five minutes, the user was given a break to stand away from the workstation. After the break, the user was asked to sit again at the workstation and put on the eye tracking glasses. For scenario B, the ambient background sound recording was integrated into the SCADA video, so they heard the ambient sound through the computer speakers as it plays. The prototype for Scenario B was started, and the user was asked to monitor the SCADA prototype again for five minutes. After the five-minute session, the user was given another break to stand away from the system.

There were six, independent, five-minute long SCADA prototypes with different warnings and alerts. Three of the SCADA prototypes had no ambient sound associated with them (Scenario A, C and E), and three of them had ambient manufacturing sound as part of the recording

(Scenario B, D, F). The users were asked to watch each of the six scenarios with a short break in between sessions. Scenario A and B were alternated, so that half the users started with scenario A and half with scenario B. Scenario C and D were alternated, so that half the users started with scenario D and half with scenario C. Scenario E and F were alternated, so that half the users started with scenario E and half with scenario F. Altering which scenario was presented first was a mitigation against order bias during the testing; the order of the testing in Table 1 was followed for each user.

Table 1

Testing Scenario Order for Users

User	1st Session	2nd Session	3rd Session	4th Session	5th Session	6th Session
1	A: No Sound	B: Sound	C: No Sound	D: Sound	E: No Sound	F: Sound
2	B	A	D	C	F	E
3	A	B	C	D	E	F
4	B	A	D	C	F	E
5	A	B	C	D	E	F
6	B	A	D	C	F	E
7	A	B	C	D	E	F
8	B	A	D	C	F	E
9	A	B	C	D	E	F
10	B	A	D	C	F	E
…						
99	A	B	C	D	E	F
100	B	A	D	C	F	E

After six sessions, the participants were free to leave the study. The eye tracking recording was then exported to the Tobii Pro Lab analysis software to gather the eye tracking metrics for the two scenarios types: No / Min Sound (A, C, E) and Ambient Sound (B, D, F) for the participant. After all 100 participants had completed the study, statistical assumptions were checked and a paired t-test was be run on the eye tracking metrics to see if there was a significant difference between the two scenario types (No / Min Sound and Ambient Sound).

CHAPTER 2

LITERATURE REVIEW

Value of a Good User Experience

Omer Qadri (2017) stated in his article *The business value of good user experience in HMI/SCADA*:

> For industrial automation systems used by various users, the focus isn't sales but it is effectiveness, efficiency, and productivity. Systems with a poor user experience can lead to the following consequences: decreased productivity, increased errors, increased training costs, decreased job satisfaction and increased employee turnover.

Iterative usability testing provides value to the final product in that it takes into account the perspective of the end user in design decisions for the layout of the user interface. This means that the screens are ultimately designed in a way that accommodates the needs of the user. If the customer can utilize the user interface in a way that is comfortable for them, then this could prevent some of the issues described by Qadri (2017).

Wood (1998) notes that "to be usable, a user interface must provide access to the functions and features of an application in a way that reflects the users' ways of thinking about the tasks that a potential application will support (Wood, 1998, pg. 2)." Usability testing provides insight into the mental model of how the customer expects the product to perform as well as their preference for key screen elements on the user interface. Wood (1998) continues to state that "this requires that the application not only provide support for necessary aspects of the users' work, but must also provide the means for them to interact with the application in ways that are intuitive and natural (Wood, 1998, pg. 2)." Designing user-centric screens can have a number of practical applications especially for petrochemical plant manufacturing monitoring and control.

SCADA

SCADA is "a type of control system that collects and displays data and allows users to manipulate and control the system from a distant location (Koffskey, 2010)." SCADA is used in various industries such as energy, food and beverage, manufacturing, oil and gas, power, recycling, transportation, and water and waste water (Gould, 2017). In the petrochemical industry, the status of individual instruments is monitored by one or a few supervisors at a central command station with a SCADA screen.

Boyer (2009) notes that "SCADA technology has evolved over the past 30 years as a method of monitoring and controlling large processes." Many of these processes can be thousands of miles in length and square miles. SCADA is a connected system of hardware and software devices that affords organizations control over their entire process on-site or remotely; allows for compiling and monitoring data in real-time; lets them use HMI software to connect apparatuses like valves, motors, sensors and pumps; and keep a record of activities and events in a log file (Boyer, 2009).

An entire petrochemical plant can be monitored at a singular location for issues that may arise anywhere on the manufacturing floor. This leads to faster response to issues and quicker escalation of mitigations. Bailey & Wright (2003) state that some of the advantages of SCADA include the following:

> The computer can record and store a very large amount of data; the data can be displayed in any way the user requires; thousands of sensors over a wide area can be connected to the system; the operator can incorporate real data simulations into the system; many types of data can be collected form the RTUs; the data can be viewed from anywhere, not just onsite.

SCADA and User-Centered Design

There are some common practices for creating a successful SCADA user interface; a cross functional team of engineers, operators and designers is needed to draft requirements, create graphics and identify the implementation strategy. Information should be consistent on the user interface; elements of the petrochemical plant should be represented the same way every time it is shown on the user interface. For example, the same icon should be used for a pump or an alarm every time that pump or alarm is shown on the user interface. The location of titles, textual information and other common labels should be consistent throughout the screen. Also, it is important that there is a well-thought out grouping of information, the screen real estate is organized and not overwhelming to view, the font and size of fonts is the same throughout, abbreviations are standardized throughout the screen, and the messages on the controller are very clear (Roessler & Garrison, 2013).

If user-centered SCADA devices are implemented, then there are several practical advantages like lesser training times, faster reactions with less errors (increases equipment security), higher productivity with much faster reaction times for the user (greater screen optimization) and higher motivation and satisfaction ratings (Copadata, 2017).

SCADA Hard and Soft Points

Kim (2010) stated that "SCADA systems typically implement a distributed database, commonly referred to as a tag database, which contains data elements called tags or points. A point represents a single input or output value monitored or controlled by the system." These points can be either hard or soft points. Hard points are those that are visual representations of ether an input or output connected to the system, and soft points are screen representations that demonstrate a logic or math operation (Dumitru & Gligor, 2012). SCADA systems contain both hard and soft points on the user interface. Figure 1 shows an example of a soft and hard point.

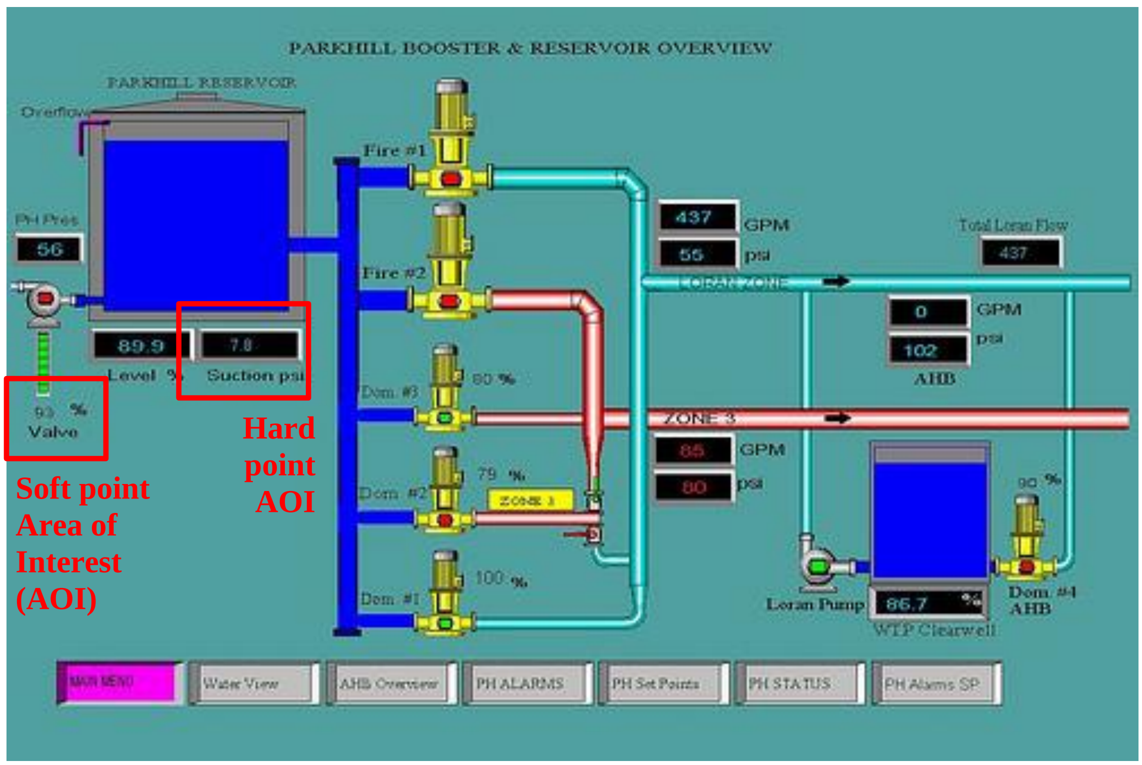

Figure 1. Example Soft and Hard Points for a SCADA system (SCADA Systems, 2017)

Building a screen with the appropriate and key information for a SCADA system is fundamental to the user in identifying if there is an issue on the manufacturing floor. It would be valuable to know if users that are monitoring a SCADA system tend to spend more of their time looking at the hard points or the soft points. This information would be beneficial for the SCADA screen developers, so they could focus on creating points that the user utilizes more. It would also be valuable to the manufacturing company, because they would identify the type of point that is valuable for their users. Lesser important screen elements could be reduced, which would therefore enhance the user experience and overall functionality of the screen.

Alarm Types: Alerts and Warnings

There are several severity levels for notifications on the SCADA interface. Warnings are a first level of notification for an issue on the user interface and are typically depicted with a yellow color. New Relic (2017) notes the following:

> A Warning threshold for an alert condition [can be monitored] when an event passes this value, but you do not want to receive an alert notification for it. In general, the Warning will be set at a threshold lower than the Critical threshold. This is because the Warning will trigger before a higher, Critical condition occurs.

A critical value or alert is defined as a next level of notification for the user. It is at this point that intervention is required on the part of the operator; alerts are generally depicted in a red color. “An alert is a signal that warns of danger (American Heritage Dictionary of the English Language, 2016).”

These warnings and alerts can be static colors or they may be blinking on the user interface to attract attention to the observer. An equal number of warnings and alerts will be utilized in the SCADA screen for the study. Also, an equal number of static and dynamic alarms will be employed on the SCADA screen as will. An example of the SCADA alerts and warnings can be seen in Figure 2.

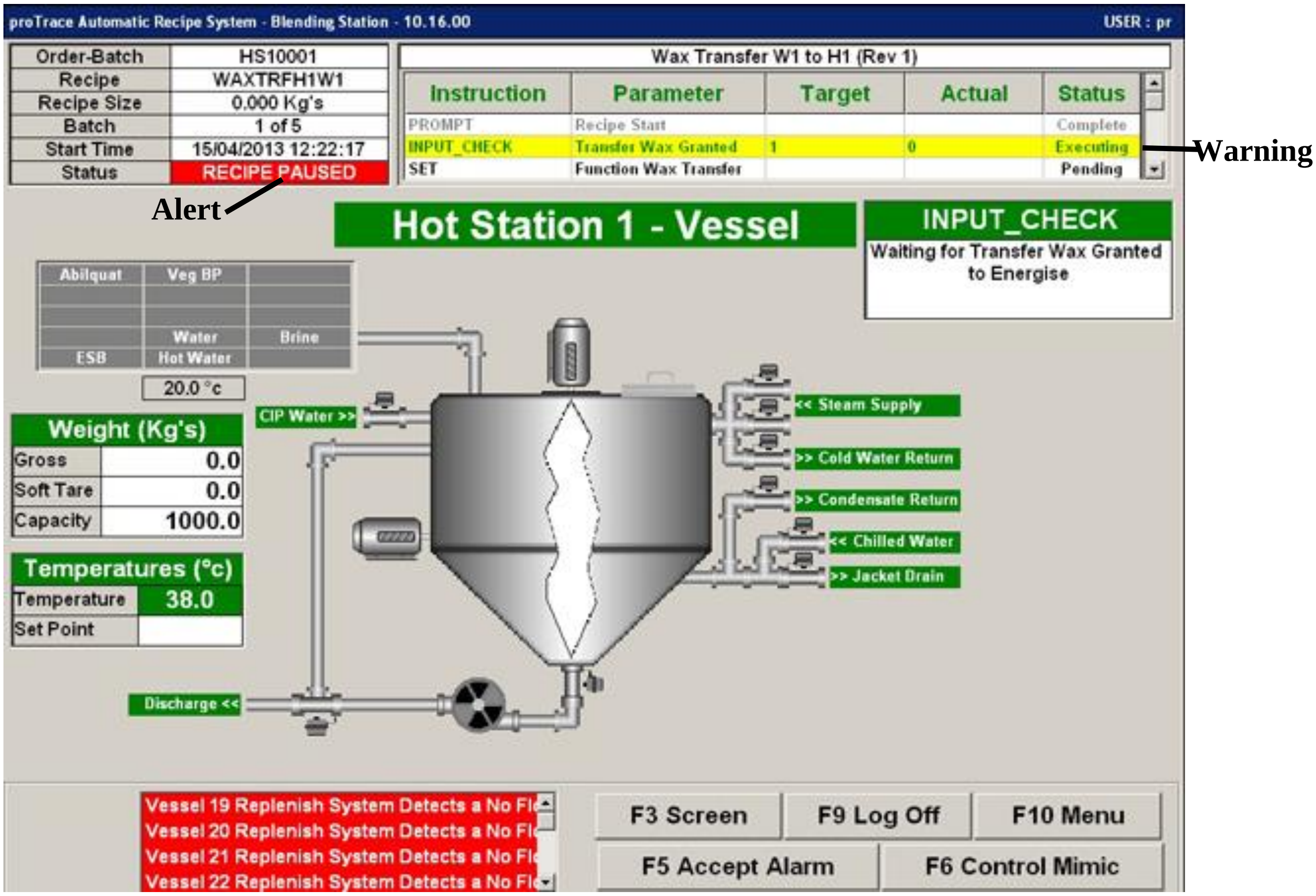

Figure 2. Example Alarms on SCADA screen (Practicon Ltd, 2017)

SCADA Display Categories

There are several types of SCADA displays including current operations, equipment control, alarm and event summaries, trends and historical reports, and maintenance displays. The current operations SCADA screens display the operating and current status of all the equipment depicted on the user interface; some examples of this may include flowrate, turbidity, stopped/running status, and percent open for valves. The equipment control SCADA screens are generally in the form of pop ups on the SCADA screens, and they provide controls to operate the equipment. Once the actions are taken, then the operator can click on Exit to close the pop up display (McCrady, 2013).

The operator can see which alarms and issues are occurring on the system through the alarm and event summaries. These are generally listed in chronological order with the timestamp of when the issue occurred. Several general fields for alerts and events include the description and tag name, time and date of issue, current state or value, status of alarm (new, return to normal, acknowledged) (McCrady, 2013).

The trend and historical reports allow the operator to see the values of a specific output over the course of a set amount of time. Generally, several outputs can be viewed at once, and the time range for the trend can be configured. The maintenance displays can be set to show the clocks in the PPCs and any failures with the communication. The overall status of the system wide plant can be viewed too from a standpoint of the percent communication failures (McCrady, 2013).

Eye Tracking

Eye tracking is a standard usability study tool to capture eye gaze and identify the mental model of a user viewing information or performing tasks on a user interface. Users tend to fixate their gaze on the information and screen elements that they deem are the most important and interesting to them in completing a task (Yarbus, 1967). Eye tracking is especially useful in identifying how the user expects the user interface to work. It is a technique used by researchers that allows for the tracking of eye movements and the order of the eye movement; this visual information allows researchers to understand how users interact with a display and ultimately leads to improved design of user interfaces (Poole & Ball, 2006).

This technique can be used to identify attentional pathway distribution on a user interface, screen elements that a user focuses on, the length of time a user spends on that particular portion of the screen, screens items that are confusing and locations where a user would expect to find specific information on the screen. By identifying where a user gazes, it also allows researchers to identify if a user is paying attention to a specific area of the screen especially if there happens to be a problematic situation (Schiessl, Duda, Thölke & Fischer, 2003). Schiessel et al. (2003) further notes that "eye movement analysis produces highly relevant data, otherwise not collectable, such as: reading behavior, cognitive workload, level of attention, viewers' entry point and level of frustration (Schiessal et al., 2003).

The first eye tracking studies occurred in the late 1870s, and the eye tracking devices required direct contact mechanically with the cornea of the eye (Jacob and Karn, 2002). One hundred years later, in the 1970s, engineering companies like Applied Science Laboratories designed and sold eye tracking units specifically to customers performing research (Holmqvist, Nyström, Andersson, Dewhurst, Jarodzka, & van de Weijer, 2011). Advances in the eye tracking technology have led to units being more portable and more powerful in the metrics they can collect and analyze.

Eye Tracking Metrics

There are many metrics that can be collected when using eye tracking. Jacobs & Karn (2002) collected the study data from twenty usability studies and identified the eye tracking metrics used in each of those studies; after an extensive analysis, they noted that some of the most common metrics and terms include fixation / gaze duration, area of interest and scan path.

A fixation or gaze point occurs when the eye slows or stops on a particular spot for a period of time. The general minimum duration of stoppage is 100-200 mS, and the velocity of the eye has decreased or has come to a full stop (Jacobs & Karn, 2002). When the eye travels between fixations or gaze points, this eye movement is called a saccade. While reading, the eye may stop on every fourth or fifth word; this is called the visual span. More experienced readers have a longer or wider visual span than novice readers; their eye has a longer saccade before hitting a fixation point. When the eye follows a moving object that is traveling at a relatively constant speed, then the eye is said to have a smooth pursuit without any saccades (iMotions, 2015).

Another common term for eye tracking is called the area of interest (AOI); this is an area or portion of a user interface or localized viewing area that is defined by the research team. It is not defined by the participant in the study (Jacobs & Karn, 2002). The AOIs for this research study will be the hard and soft points for the user interface. The overall number of soft and hard points will be the same, and the total area of the soft points will be equal to that of the hard points.

The gaze or fixation duration is generally described with respect to an AOI; it is the total duration of time the eye has spent viewing an AOI for a particular study. The fixation duration consists of a number of consecutive fixations all with a localized area within that AOI. The gaze duration can also include several short saccades between those fixations. When a fixation occurs outside the AOI, then this is the end of the gaze or fixation duration. Other terms for gaze duration include dwell, glance and fixation cycle. Gaze duration is the dwell time divided by the fixation count, and gaze percentage is the dwell time divided by the overall length of the test (Jacobs & Karn, 2002).

Further research has determined that the gaze duration is directly linked to the time it takes the participant to fully process the meaning of the text. A higher cognitive load will result in higher gaze durations (Irwin, 2004). Since the user has to interpret hard and soft points differently, there is expected to be a potential difference in the gaze duration for these two types of screen elements. Using the eye tracking system, an area of the screen can be identified as an AOI. The analytics software package will then capture metrics for that AOI.

Koffskey (2010) further defined three parameters for eye tracking for her study on a SCADA interface (Fixation Frequency per AOI, Gaze Duration Mean per AOI and Gaze Percentage per AOI). These metrics are of interest, because they combine the learning from Jacob and Karn (2002) with a study on SCADA interfaces. Fixation Frequency per AOI is defined as the total count of fixation counts (number of times participant's eye entered the AOI from the background area of the screen) divided by the AOI visible time (time that the AOI was actively collecting statistics). Gaze Duration Mean is the dwell time divided by the fixation count (Koffskey, 2010). Dwell time is considered to "start at the moment the AOI is fixated and ends at the moment the last fixation on the AOI ends = the sum of durations from all fixations and saccades that hit the AOI" (SensoMotoric Instruments, 2011a). Gaze Percentage per AOI is the overall total dwell time for a particular AOI divided by the total time of the study (Koffskey, 2010).

While durations and counts provide metrics for a particular participant, in some cases, it is also important to identify the order in which users view particular points on a screen. A Scan Path is defined as "a spatial arrangement of a sequence of fixations (Jacobs & Karns, 2002)." Noton & Stark (1971) were the first to create the term of scan path, and they noted that when a particular visual area is viewed, the eye performs a series of movements, and the sequence of those movements can provide information about the visual memory of the participant's viewing. The scan path contains gaze-direction, fixation duration and position direction, and saccade duration (Noton & Stark, 1971).

Analyzing the Eye Tracking Data

Gaze plots are visualizations of how the participant viewed an area; they show the fixation locations and durations, saccades and the overall scan path for a user. The overall key function of the gaze plot is to show how long and where each participant looked throughout the study. Fixations are recorded with a sequential number throughout the course of the study, and the saccades connect each fixation with a line. The fixation duration is represented by a circle around the fixation number. The larger the diameter of the circle is, the longer the fixation duration (Tobii, 2017).

Figure 3 shows an example gaze plot for the McDonalds Twitter page. The fixations are labeled 1-18 in orange circles, and the saccades are shown in orange lines between the fixation circles. The fixations are labeled 1 through 18, because this was the order that the participant viewed them throughout the study. The circle for 14 is much larger than that of the circle for number 3, because the fixation duration was longer for fixation 14 than that of number 3. The user spent more time looking at 14 than they did looking at number 3.

Figure 3. Gaze Plot Example (Redwood, 2015)

Another common tool for viewing the areas of focus for a set of participants in a study is to create a heat map of the data from the study. These heat maps do not show the scan path or order of the fixations, but the heat map can show the visual attenuated focus for several hundred participants all at once (Tobii, 2017). An example of a heat map can be seen in Figure 4. This heat map has areas of green (quick or short focus), yellow (further, slightly longer focus), and red (if the user or multiple users have spent a much longer duration focusing on that portion of the screen). This type of plot will be helpful for collating the data from all the participants in the research for this study and noting the general areas on the SCADA user interface that drew the attention of the participants overall.

Figure 4. Heat Map Example (Redwood, 2015)

SCADA and Eye Tracking

There have been very few connections of SCADA with eye tracking in literature. A study was conducted to determine if there is a correlation between eye reaction time and gender, age, screen element color or screen elements location on a SCADA application. It was determined that males have a faster reaction time when responding to stimuli on a SCADA screen than women; it was found that this is due to the difference in masculine and feminine visual processing systems. The reaction time of males was slower than women when the visual images became more complex on the SCADA screen (Gervasi, Murgante, Misra, Borruso, Torre, Rocha, Taniar, Apduhan, Stankova & Cuzzocrea, Eds., 2017).

Also of interest in the study was that there was a difference in the reaction time of younger and older participants. Older participants had slower reaction times than younger participants, and older users' reaction time was slower than younger participants when the visual stimuli became more complex (Gervasi et al., 2017).

As far as screen element color, users had a faster reaction time to yellow being used for a STOP button than to that of green or red. Since red and yellow are considered to be indicators of alerts and warnings, this tends to make sense that yellow would cause a faster response time than green. Green is generally a status indication of safety and that no intervention is needed by the operator. It was proposed in the study that participants had a faster response time for yellow over red, because yellow has a greater luminosity and visibility than red. Also, humans tend to have higher sensitivity of vision peaks for the yellow part of the spectrum than that of red (Gervasi et al., 2017).

For the position of screen elements on the SCADA screen, it was determined that there was a faster reaction time to screen elements located on the left hand side of the screen. This finding is explained by how users tend to read text from left to right, which is the natural reading order (Gervasi et al., 2017).

The importance of this study is that participant demographics and screen design have an impact on eye behavior and reaction time. Because of this, it will be fundamental to the research study to include a wider range of ages and both genders as participants. Also, it is important to locate hard and soft points on both the left- and right-hand side of the screen and to include an equal mix of green, yellow and red as part of these two types of points.

Another study was performed to identify if there is a difference in the eye movement and visual monitoring strategy between expert and novice operators when watching a SCADA screen for a Crude Refinement simulation. In her experiment, she focused on the use of scan paths to identify how operators watch the SCADA screen as well as the following eye tracking metrics: Fixation Frequency per AOI, Gaze Duration Mean and Gaze Percentage per AOI (Koffskey, 2010).

It was found that expert operators did have a different strategy for monitoring a SCADA interface. They tended to have a scan path that frequently gazed to critical areas of the SCADA interface. Experts also tended to have a higher Gaze Percentage per AOI on the temperature and flow values, which were critical values for the petrochemical manufacturing plant. It was recommended in the text that expert eye movement behavior could be identified and then used to modify the training program for novices to bring them to the expert level faster. This training would allow the novice operators to learn to scan areas of the SCADA screen that depict high risk areas and therefore identify issues faster (Koffskey, 2010).

She concluded that operators had a much higher attention level when the SCADA screen included active alarms; for this reason, the SCADA screen should be designed in such a manner as to reduce visual strain on the operator and his/her attention. She noted that the participants that were using the more muted and grey backgrounds were able to identify the set points much more quickly than operators that were looking at a much brighter background color scheme (Koffskey, 2010).

The importance of this study is that it noted that operators of different skill levels viewed the SCADA screen differently based on their experience. For this reason, it is important to take into account a participant’s familiarity of manufacturing and the general process represented on the SCADA interface. She also identified that a SCADA user interface with a muted background allowed for a quicker response time to set points. Because of this, the background color to be used in the SCADA designs for this research study will also be of a grey or more muted color in order to reduce the interference of the background color with the identification of the hard and soft points. She also notes that alarm activity heightened the visual attention of the participants. For this reason, the SCADA interface to be used in this research study will include dynamic alerts and alarms to mimic a real-world setting.

As part of working in the petrochemical industry, operators must manage alarms and other safety issues while using very complex SCADA user interfaces. A team of researchers wanted to assess human performance with two user interfaces designs (blue and grey) as well as three workload levels (hard, medium and easy). Several tools were used to monitor the participants including eye tracking. A total of twelve participants were studied via one simulation with three levels of workload; the workload was modified by increasing or decreasing the number of issues (failure events) on the SCADA interface (Ikuma, Harvey, Taylor & Handal, 2014).

There was a difference in the eye tracking gaze duration based on differences in workload level but not background color (grey or black). The overall percentage of time the operators spent looking at portions of the screen changed based on various workload levels. Users in higher workload situations tended to focus on alarming areas of the screen, while users in lower workload situations tended to scan the screen looking for issues (Ikuma et al., 2014).

The importance of this study is that the workload level will have an effect on the outcome of what areas of the screen the user tends to focus on. For this reason, it is important to identify one level of workload for the entire study for the simulation. Since users had two very different gaze durations at the extremes of the workload level, a workload level of medium difficultly will be chosen for the research study. This will include a combination of alarms and steady state monitoring for the SCADA interface.

For the Idaho National Laboratory, they have integrated eye tracking into their Nuclear Reactor Instrumentation and Control SCADA system as an effort to create a digital framework for a control system that will not only assess the performance of the nuclear reactor but also that of the human operator. The purpose of this is to ensure reaction times for the operators are appropriate for the workload level of the nuclear reactor plant. The ultimate goal of the prototype devised by the Idaho National Laboratory is to increase the overall efficiency, reliability and safety for the nuclear reactor plant (Dudenhoeffer, Tran, Boring & Hallbert, 2006).

A team from the Korea Atomic Energy Research Institute also incorporated eye tracking into their SCADA system as part of a human factors usability study to analyze the current state of the SCADA interface for a nuclear power plant. The new testing methods and lab were called the Integrated Test Facility. The team created the lab in an effort to measure and analyze the cognitive and physical workload of the operators monitoring the SCADA screens at the nuclear power plant. Based on the results of their studies, they plan to update the list of primary tasks for the user and the requirements associated with each task (Oh, Lee, Lee & Sim, 1998).

Another team created a four-part supervisory system that allowed for the supervision of multiple automated unmanned aerial vehicles. There were four parts to the prototypical supervisory equipment: the unmanned aerial vehicle current SCADA system, an eye tracking system for the operators who watch the SCADA system, an analysis tool and a visual display for peripheral monitoring. The prototype was evaluated by experts after it was completed to assess its value to the command supervisor. The results of the evaluation demonstrated that the prototype would provide value to the command supervisor for the monitoring of multiple automated aerial vehicles (Fortmann, Muller, Ludtke & Boll, 2015).

A team from the German Research Center for Artificial Intelligence described a prototype factory called the Smart Factory that incorporates multiple future intelligent technologies in order to maximize the overall efficiency and throughput of the factory. The Smart Factory is flexible, expandable and modifiable, and it can be connected or networked to several manufacturing companies directly. The factory concept is automated, and its multiple components work in concert to complete context-specific tasks, and the Smart Factory is very user-friendly (Meixner, Petersen & Koessling, 2010).

The team reviewed the application of several different methodologies for user interaction to assess their utility and usability in terms of the Smart Factory, such as Augmented Reality and eye-tracking capabilities. The team then developed a mobile application that could communicate with various components of the manufacturing plant utilizing these technologies to better network the lab components and theoretically make the laboratory more efficient (Meixner et al., 2010).

Noise and Distraction

There have been linkages in literature between background noise and its distracting effect on being able to perform tasks. Banbury, Tremblay, Macken and Jones (2001) state that “the ‘irrelevant sound effect’ in short-term memory is commonly believed to entail a number of direct consequences for cognitive performance in the office and other workplaces (Banbury, Tremblay, Macken, & Jones, 2001).” This translates into the idea that background noise can affect how workers think and perform tasks in the work environment. Further, they state that “these studies established that the degree of interference depends on the properties of the irrelevant sound as well as those of the cognitive task (Banbury et al., 2001).”

In another study, users were presented with performing a very high vigilance task for an hour with music and then again with white noise (both at the same amplitude), and they calculated the number of tasks completed versus false alarms. It was identified that when listening to the white noise, the users had a higher degree of distinguishability between the positive hits and the false alarms. This leads to the conclusion that user may have been distracted by the words and musical melody over the general amplitude of white constant noise. The authors note that the users performing the tasks may have been spending some of their concentration deciphering the context and meaning of the songs instead of focusing their attention on the high vigilance task (Hartley and Williams, 2007).

Trista'n-Hernandez, Pav'on-Garcia and Campos-Canton (2017) have noted in their article that noise has a negative effect on academic and work performance. The team studied the brain wave patterns of a set of participants that performed a task in silence and then again with background white noise and found the following (Trista’n-Hernandez et al, 2017):

> The results show significant decreases in both beta and theta frequency bands under background noise exposure. Since attentional improvement is related to an increment on amplitude of both beta and theta bands, it is suggested that decreases on amplitude of these frequency bands could directly be related to a lack of attention caused by the exposure to background noise.

European Agency for Safety and Health at Work (2005) states that noise at work can harm a worker’s health, including increased stress, loss of hearing and risk for safety accidents. Some of the risks of increased noise levels lead to an environment that is difficult for employees to understand and hear words and signals, hear a danger or warning approaching, be distracting overall, and increase stress and cognitive load. This can ultimately lead to a higher level of errors occurring on the job. Some of the factors that affect the stress on the worker include the amplitude, frequency and predictability of the sound and the task complexity in general (European Agency for Safety and Health at Work, 2005).

While some journals note the negative effect of noise on worker's attention and cognitive ability, there have been several studies that show that noise can have a positive effect on the workplace as well. Rodriguez (2017) conducted a study of noise and manufacturing floor productivity. The study was conducted to determine if there is a correlation between music tempo and the efficiency of producing product on the manufacturing floor. Thirty different assembly line workers were exposed to white noise, slow tempo music and fast tempo music, and the results show that efficiency is positively correlated with the tempo (up to a point). At a very fast-paced tempo, the work efficiency begins to decrease (Rodriguez, 2017).

In another journal article, the authors study how sound amplitude affects creativity. White noise at low, medium and high amplitudes was played for a set of participants that were performing several creative tasks. The users were more productive at completing their creative tasks at the moderate level of sound versus the low level of sound. The very high amplitude of sound negatively affected creative performance (Mehta, Zhu and Cheema, 2012). Mehta et al. (2012) note that at the moderate amplitude, users had a better aptitude to "processing difficulty, inducing a higher construal level and thus promoting abstract processing, which subsequently leads to higher creativity." Further, they noted that "a high level of noise, however, reduces the extent of information processing and thus impairs creativity (Mehta et al., 2012)."

CHAPTER 3

METHODOLOGY

Research Questions

Is there a difference in user eye behavior (Time to First Fixation, Fixation Frequency per AOI, Gaze Duration Mean, and Gaze Percentage per AOI) between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface?

Hypotheses

<u>Time to First Fixation</u>:

$\mu_{1A} = FN_{(t1)}AN_{(1)}$; $\mu_{2A} = FN_{(t2)}AN_{(2)}$

H_{0A}: $\mu_{1A} = \mu_{2A}$, Null: There is no statistical difference in the Time to First Fixation between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface.

H_{1A}: $\mu_{1A} \neq \mu_{2A}$, Alternative: There is a statistical difference in the Time to First Fixation between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface.

Fixation Frequency per AOI:

$\mu_{1B} = FN_{(n1)}/AOI/AN_{(1)}$; $\mu_{2B} = FN_{(n2)}/AOI/AN_{(2)}$

H_{0B}: $\mu_{1B} = \mu_{2B}$, Null: There is no statistical difference in the Fixation Frequency per AOI between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface.

H_{1B}: $\mu_{1B} \neq \mu_{2B}$, Alternative: There is a statistical difference in the Fixation Frequency per AOI between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface.

Gaze Duration Mean:

$\mu_{1C} = GD_{(t1)}AN_{(1)}$; $\mu_{2C} = GD_{(t2)}AN_{(2)}$

H_{0C}: $\mu_{1C} = \mu_{2C}$, Null: There is no statistical difference in the Gaze Duration Mean between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface.

H_{1C}: $\mu_{1C} \neq \mu_{2C}$, Alternative: There is a statistical difference in the Gaze Duration Mean between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface.

<u>Gaze Percentage per AOI</u>:

$\mu_{1D} = GP_{(1)}/AOI/AN_{(1)}$; $\mu_{2D} = GP_{(2)}/AOI/AN_{(2)}$

H_{0D}: $\mu_{1D} = \mu_{2D}$, Null: There is no statistical difference in the Gaze Percentage per AOI between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface.

H_{1D}: $\mu_{1D} \neq \mu_{2D}$, Alternative: There is a statistical difference in the Gaze Percentage per AOI between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface.

Population

Using the sample size calculator in Figure 5, the expected sample size was 267 with a 5% margin of error and 90% confidence level (100 participants with three replicates each for a total of 300 data points).

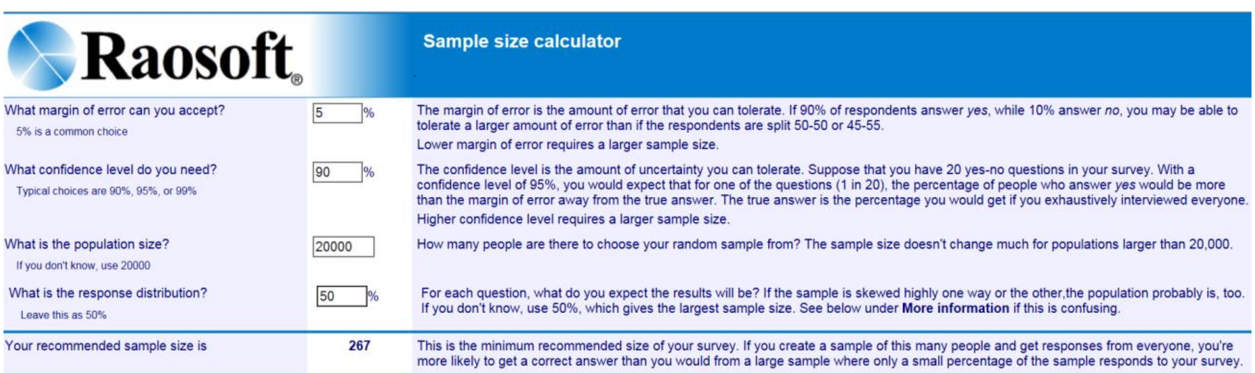

Figure 5. Sample Size Calculator (Raosoft, 2004)

Data Collection Procedures

SCADA prototypes were created in Microsoft PowerPoint; this was done by creating 60 individual slides to depict the functional petrochemical manufacturing SCADA screens and the set points, warnings and alerts on the screen. The 60 slides were placed in Windows Movie Maker and each slide held for a duration of five seconds; this provided 300 seconds or five minutes of a dynamic SCADA prototype. This process was repeated, so that there were a total of six, five-minute SCADA prototypes.

This type of prototyping is a common tool used in the development of front-end user interfaces for usability testing. This allowed for the construction of dynamic user interfaces without the use of software coding; this offered advantages in that functioning prototypes could be created for usability testing without the software development time.

The prototype was dynamic in that set points changed over the course of the test, and alarms and warnings occurred throughout the test as well. Alarms are values that are out of range, and the warnings are those values that are near an out-of-range value. Alarms were depicted with a red indication, while a warning was shown with the color of yellow. The overall design of the SCADA was based on examples from websites such as Reliance.SCADA.com, Tyconautomation.com, Nishcon.com, Wonderware.com or Fultek.com.

A snapshot of the first frame of one of the SCADA prototypes is shown in Figure 6; all setpoint values were in range and highlighted in the green boxes in Figure 6 (i.e. 0.3 bar, 0%, 3 L/h, etc.). Values for the setpoint readings changed over the period of five minutes, and they turned yellow for warnings and red for alerts. A snapshot of the last frame of one of the videos can be seen in Figure 7; the alerts and warnings were the setpoints highlighted as red (i.e. 29°C, -0.1 bar) and yellow (1%). There were six unique five-minute videos for the experiment.

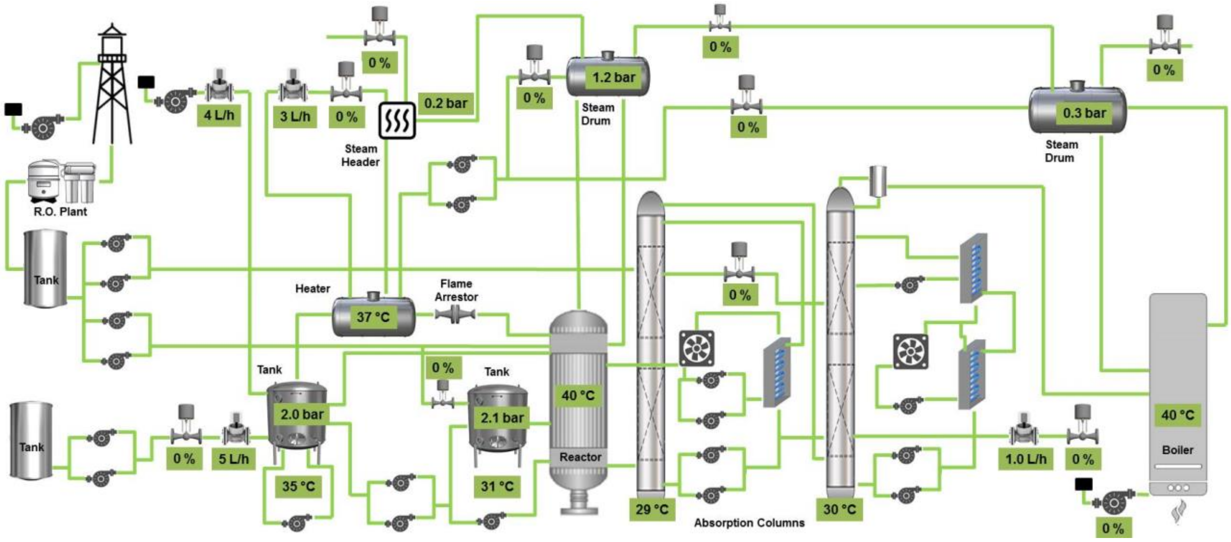

Figure 6. Snapshot of the first frame of one of the prototype videos

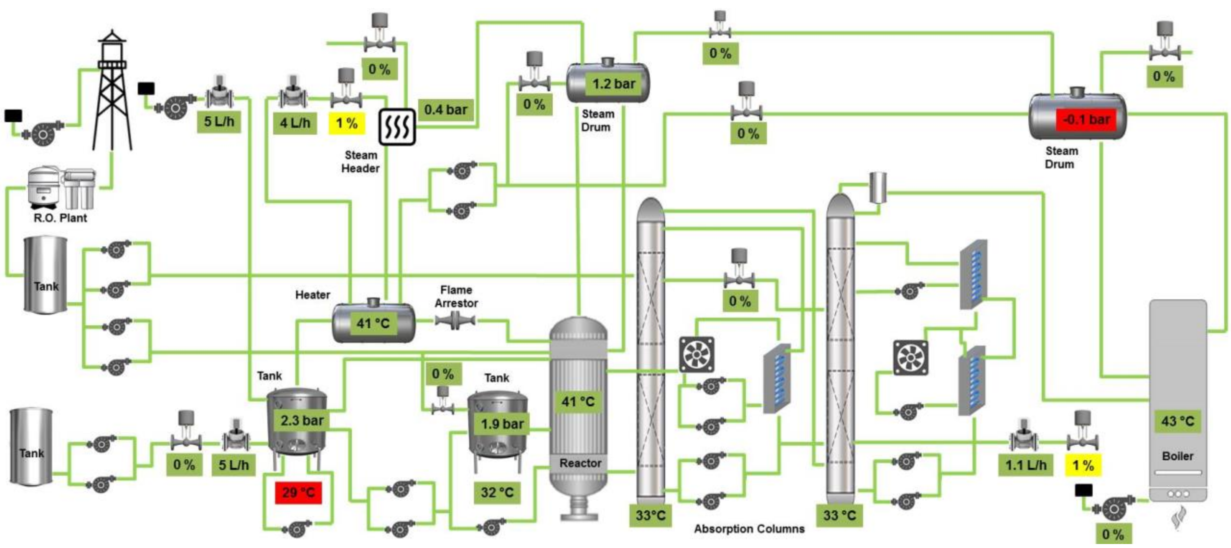

Figure 7. Snapshot of the last frame of one of the prototype videos

The ambient sound recording was purchased from Sounddogs.com for $8.81, and it is called ‘Industry Refinery Petroleum Refinery factory - Constant Machinery Road Ambience (Sounddogs.com, Industry Refinery, 2018).’ The ‘Sound Effects End User License Agreement’ noted that once purchased, the sound could be used for “Training, Educational, Marketing and

Trade Show presentations (Sounddogs.com, Sound Effects, 2018)." The sound recording was imported in Windows Movie Maker and added to three of the six SCADA prototypes. There were three SCADA prototypes with no sound and three SCADA prototypes with an ambient manufacturing sound.

The Tobii Pro Eye Tracking Glasses 2 system consisted of a wearable set of eye glasses that identify where on the user interface the users were looking; a picture of the wearable glasses can be seen in Figure 8. Tobii (2017) notes that the glasses are a "wearable eye tracker designed to capture natural viewing behavior in any real-world environment while ensuring outstanding eye tracking robustness and accuracy (Tobii Pro, 2017)."

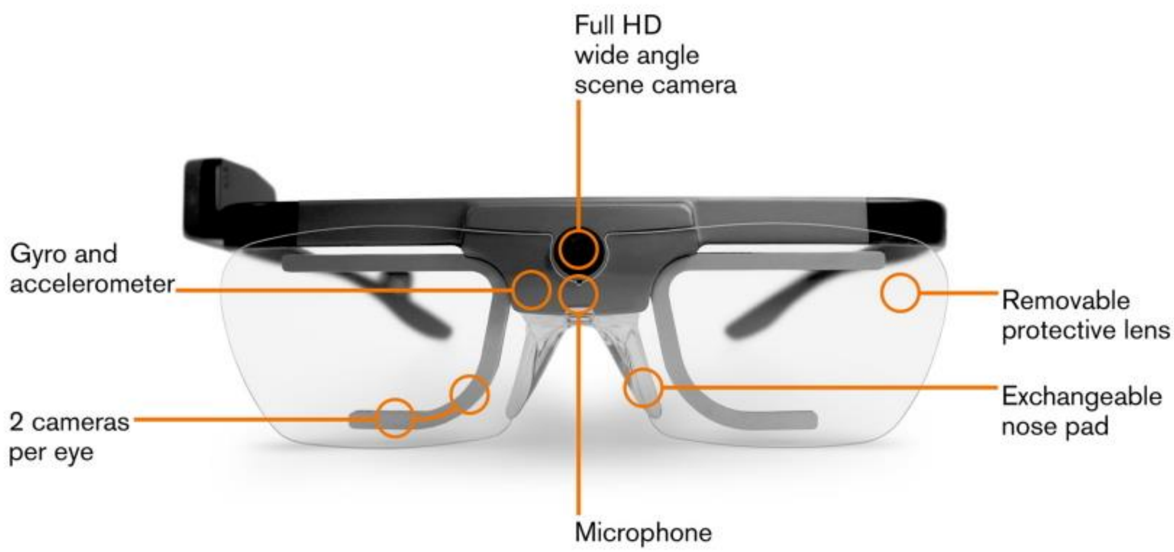

Figure 8. Tobii Pro Eye Tracking Glasses 2 (Tobii, 2017)

The Tobii Pro eye tracking system also included Tobii Pro Lab Software to analyze gaze attenuation and span paths with tools like heat maps and gaze plots. The software analysis was used to combine the data from multiple participants to determine statistics for the user sample set.

Raw data from the analysis software was exported to an Excel document for analysis in a statistical tool like SPSS.

Users wore the Tobii Pro Eye Tracking Glasses 2 system and were asked to view the SCADA dynamic prototype on the user interface for 5 minutes. The laptop was connected to a 22 inch monitor, and the users' eyes were approximately 1.5-2.0 feet away from that display. The SCADA prototype with dynamic alerts and warnings was started, and the users' eye behavior was tracked with the eye tracking unit. The order of the scenarios as depicted in Table 1 for the six SCADA prototypes was performed – each with a break after the user viewed a five-minute SCADA prototype. The treatment was the sound recording from a manufacturing area; this sound recording includes noise typical of a petrochemical manufacturing plant (environment, machine and manufacturing noises). There were speakers attached to the computer, so that the three SCADA prototypes with sound were heard while the SCADA prototypes ran.

A training was provided to explain the function of the SCADA interface. Also, a set of instructions were read to the participants to provide background before the users are exposed to the dynamic SCADA prototype (see Appendix 2). The participants filled out a demographic form to see if they fit the requirements for testing (see Appendix 3 for the demographic form and required demographic form responses in order to participate in the study). Participants had a science, engineering, or manufacturing background (work experience or technical training in one of these three fields). The participant age range for the study was 25 to 60 and included both men and women. The participants allowed to perform the study acknowledged in the demographic form (Appendix 3) that they did not have any identified hearing impairments and they had 20/20 vision.

A paired t-test was to be run to identify the differences in the Time to First Fixation, Fixation Frequency per AOI, Gaze Duration Mean, and Gaze Percentage per AOI between the user sessions with no (minimal) sound and those with the sound recording.

Variables

The variables for the study are shown in Table 2, and all have priority or importance to the research. The type of background sound was the independent variable, and the levels were either no (minimal) or the ambient sound recording. The type of background sound was a primary factor and is fixed and categorical. The resulting dependent variables were those as measured with the Tobii Pro system and analysis software. The Time to First Fixation, Fixation Frequency per AOI, Gaze Duration Mean and Gaze Percentage per AOI were the dependent variables, and they were all quantitative, interval or continuous. The precision of these dependent variables was +/- 0.1. The calculations for each of these variables are described in Chapter 2 of this dissertation.

Table 2

Variables in Assessment

Variable name and description	Units	Accuracy, precision, and/or effect size.	Range or levels	Experimental control	Other
Type of background sound	No Units	N/A	No (minimal), ambient sound recording	Primary factor / independent variable (fixed)	Categorical / Fixed
Time to First Fixation	sec	+/- 0.1	N/A	The dependent variable or response	Quantitative / Interval / Continuous

Table 2 (Continued)

Variables in Assessment

Variable name and description	Units	Accuracy, precision, and/or effect size.	Range or levels	Experimental control	Other
Fixation Frequency per AOI	1 / sec	+/- 0.1	N/A	The dependent variable or response	Quantitative / Interval / Continuous
Gaze Duration Mean	sec	+/- 0.1	N/A	The dependent variable or response	Quantitative / Interval / Continuous
Gaze Percentage per AOI	%	+/- 0.1	N/A	The dependent variable or response	Quantitative / Interval / Continuous

Type I Error

Assuming the sample size (N) and the population effect size (d) remains constant, the alpha level (Type I error) increases as the beta level decreases (Type II error). The equation for the statistical power and relation between alpha and beta is $\rho = \alpha = 1 - \beta$. Warner (2013) stated the following:

> Usually researchers set the nominal alpha level at .05. In theory, statistical power can be increased by raising the alpha level to $\alpha = .10$ or $\alpha = .20$. However, most researchers are unwilling to accept such high levels of risk of Type I error and, therefore, prefer changing

other features of the research situation (rather than increasing α) to improve statistical power.

Since the alpha level is the risk of rejecting the null hypothesis when the null hypothesis is actually true, researchers would want the alpha to be as small as possible. While a smaller alpha means less chance for a type I error (more conservative), it also means more chance for a type II error. A small alpha also means a smaller power size, which is a reduction in probability that your test will find a statistically significant difference when such a difference actually exists. A larger alpha will result in a larger power size, but the sample size will also need to be increased. This will mean more participants and will make the study cost more in the end.

Warner (2013) defines effect size as "an index of the strength of association between two variables or of the magnitude of the difference of the means." Warner (2013) further states "as the magnitude of the population effect size, d, increases, statistical power tends to increase, and the risk of committing a type II error decreases." Effect size is independent of sample size. Any increase in the sample size will result in the need for more participants.

Research Questions

If the p value was significant for any of the four dependent variables, then the participants had different eye behavior when viewing warnings and alarms when there is an absence or the presence of background sound. If this were true, then it could be said for the SCADA design used in this research that the users were tending to be distracted by either no (minimal sound) or by the presence of ambient background noise in monitoring their petrochemical plant.

It was hypothesized that the presence of the ambient background noise would be a distraction to the users, and this would cause any of the following scenarios to occur when ambient sound is present:

1. The Time to First Fixation was longer: It took the user longer to identify that a warning or alert is occurring.
2. The Fixation Frequency per AOI was lower: The user became distracted and had less eye fixations on the AOIs (warnings and alerts). Their gaze was less prevalent on the AOIs.
3. The Gaze Duration Mean was lower: The user became distracted and spent less time looking at any one point on the screen. Their gaze wandered quickly from place to place on the screen.
4. The Gaze Percentageper AOI was lower: The user became distracted and didn't spend time looking at the AOIs (warnings and alerts). Their gaze was less prevalent on the AOIs.

If the ambient background sound caused a distraction to the user, then this would be valuable information to provide to the operator and manufacturing staff. It would be imperative to provide a sound-insulated environment to the SCADA operator, so that operators could be more effective in identifying warnings and alerts on the screen.

Statistical Techniques

A paired t-test was to be used as the statistical technique for this research investigation. Warner (2013) defines this test as the following:

It provides information about the magnitude of difference between a sample statistic and the corresponding value of the population parameter that is given in the null hypothesis in number of standard errors.

In this case, data was collected for both scenarios of no (minimal) noise and background ambient noise for each participant, and the four dependent variables were calculated for both the of those two scenarios. The overall set of data from all the participants for the no (minimal) sound was compared against that of background ambient noise, and a p value was calculated. If the p value was less than 0.05, then the null hypothesis would be rejected in favor of the alternative hypothesis.

Since there were four dependent variables, if any of the four dependent variables had a p value less than 0.05, then the corresponding null hypothesis would be rejected in favor of the alternative hypothesis. This meant that if the p value was less than 0.05 for Time to First Fixation, Fixation Frequency per AOI, Gaze Duration Mean or Gaze Percentage per AOI, then it would be deemed that there was a difference in the eye behavior for viewing warning and alerts when there is no (minimal) sound versus background ambient noise.

Statistical Assumptions

Normal Distribution:

The difference between the dependent variable pairs should have normal shapes to their distribution (i.e. Time to First Fixation for a sample data point for Sound was subtracted from the Time to First Fixation for a sample data point for No Sound). A histogram was created of the difference, and the shape was assessed for skewness (|skewness| approx. < 0.8) and kurtosis (|kurtosis| approx. < 2.0)

<u>Outliers</u>:

The boxplot graphs of categorical (IV) was plotted against the dependent variables, and all outliers were identified as numbered data points on the plot. The graphs were visually inspected for data points that "lie outside the area of the plot that contains most of the data points (Warner, 2013)." Also, the regression standard predicted value was plotted against the regression standard residual in a scatterplot, and the graph was visually inspected to note the presence of outliers as well as for heteroscedasticity. Due to the limitations of SPSS in not providing a Pitman-Morgan test, Levene's Test of Equality of Error Variance was performed to note if the variances are equal. Mudholkar, Wilding and Mietlowski (2003) note that the "Pitman-Morgan test is known to be optimal for testing equality of the variances of components of a bivariate normal vector;" this test is designed for correlated or related sample sets. If the assumptions were not met, then alternative statistical methods besides a paired t-test would be employed based on which assumption were found to be invalid.

CHAPTER 4

FINDINGS AND ANALYSIS OF DATA

Summary

This chapter describes the assessment of the statistical assumptions and discusses the results for each of the hypotheses. The subsequent conclusions are discussed in Chapter 5.

Statistical Assumption Results

Normal Distribution:

The skewness and kurtosis can be seen in Table 3. The absolute value of all four variables (difference distributions) was less than 0.8, but the absolute value of all the kurtosis values was not less than 2.0. The kurtosis value for 'DIFF_Fixation_Frequency_per_AOI' was 4.566. All variables had an N of 1212.

Table 3

Descriptive Statistics for Dependent Variable Residuals

Dependent Variable	Min.	Max.	Mean	Std. Dev.	Skewness Statistic	Skewness Std. Error	Kurtosis Statistic	Kurtosis Std. Error
DIFF_ Time_to_ First_ Fixation	-9.01	9.74	-.256	3.08	0.065	0.07	0.945	0.14

Table 3 (Continued)

Descriptive Statistics for Dependent Variable Residuals

Dependent Variable	Min.	Max.	Mean	Std. Dev.	Skewness Statistic	Skewness Std. Error	Kurtosis Statistic	Kurtosis Std. Error
DIFF_ Fixation_ Frequency_ per_AOI	-2.57	0.86	0.001	0.33	-0.204	0.07	4.566	0.14
DIFF_ Gaze_ Duration_ Mean	-0.93	0.99	0.021	0.31	-0.055	0.07	0.645	0.14
DIFF_ Gaze_ Percentage_ per_AOI	-0.04	0.06	0.022	0.02	-0.106	0.07	-0.619	0.14

The distribution of the four variables can be seen in Figures 9, 10, 11 and 12, and all the graphs had a centered distribution (as was noted by their skewness values). The difference distribution for Fixation Frequency per AOI (Figure 10) had a higher kurtosis value (> 2.0) and was leptokurtic, which meant the histogram of the variable had a taller and narrower peak. Due to this kurtosis value, there was expected to be a higher percentage of outliers than a normal distribution of samples.

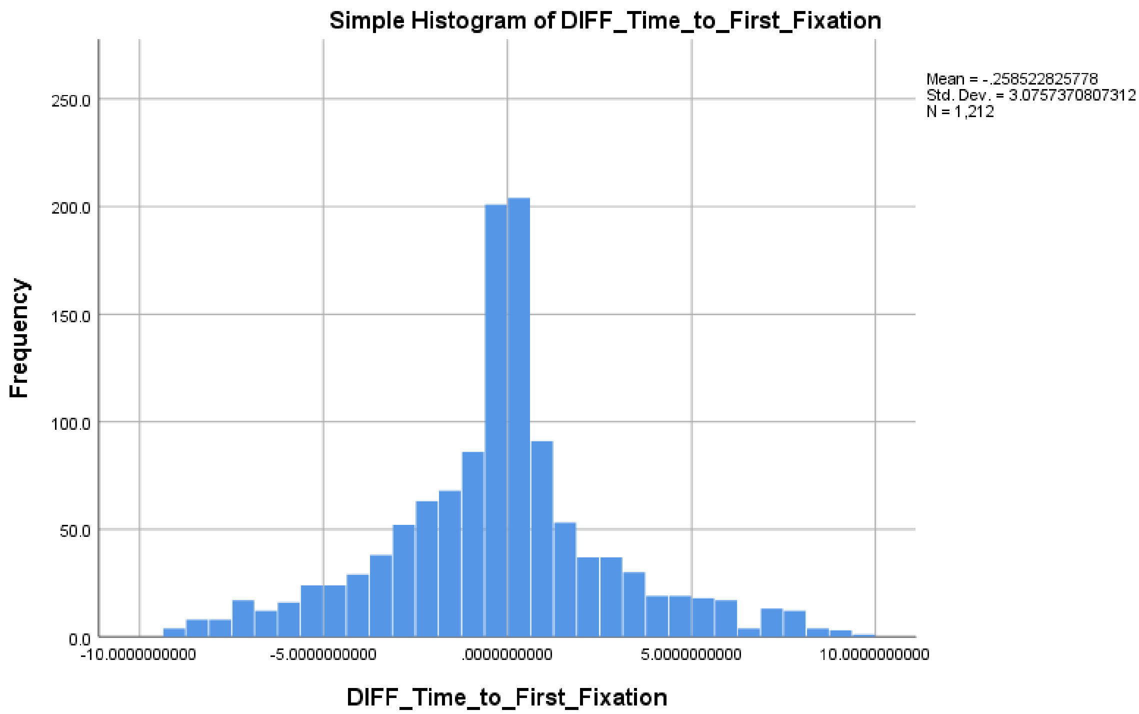

Figure 9. Histogram Distribution of the Time to First Fixation Difference Distribution (DIFF_Time_to_First_Fixation)

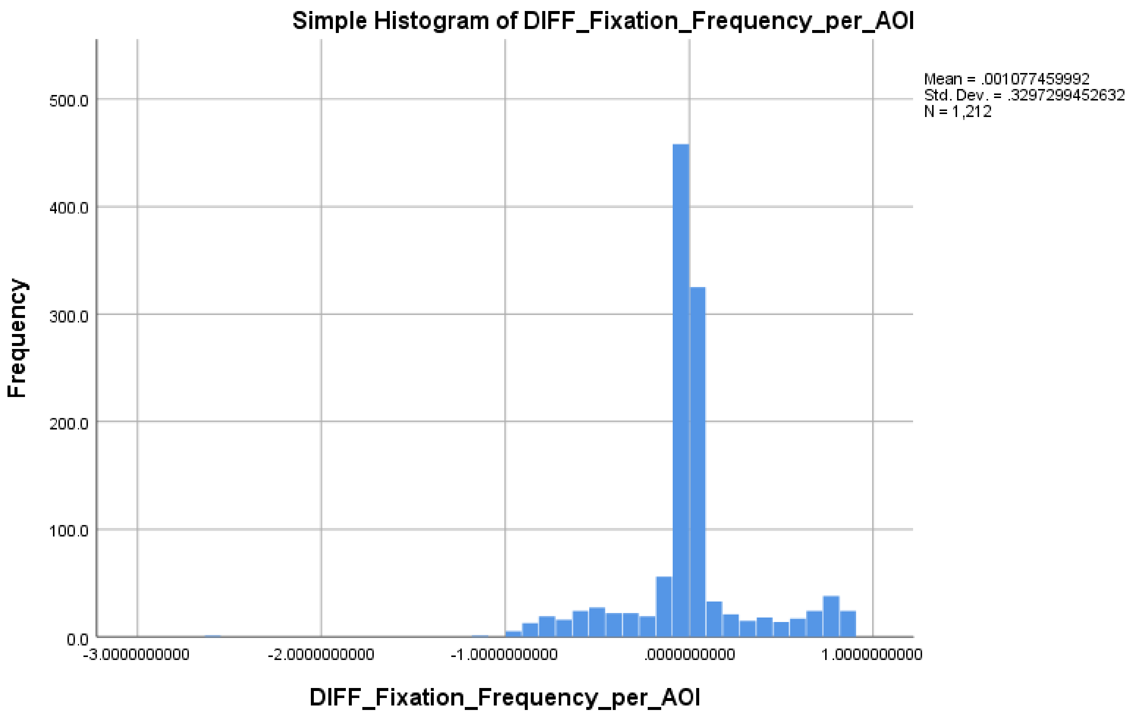

Figure 10. Histogram Distribution of the Fixation Frequency per AOI Diff. Distribution (DIFF_Fixation_Frequency_per_AOI)

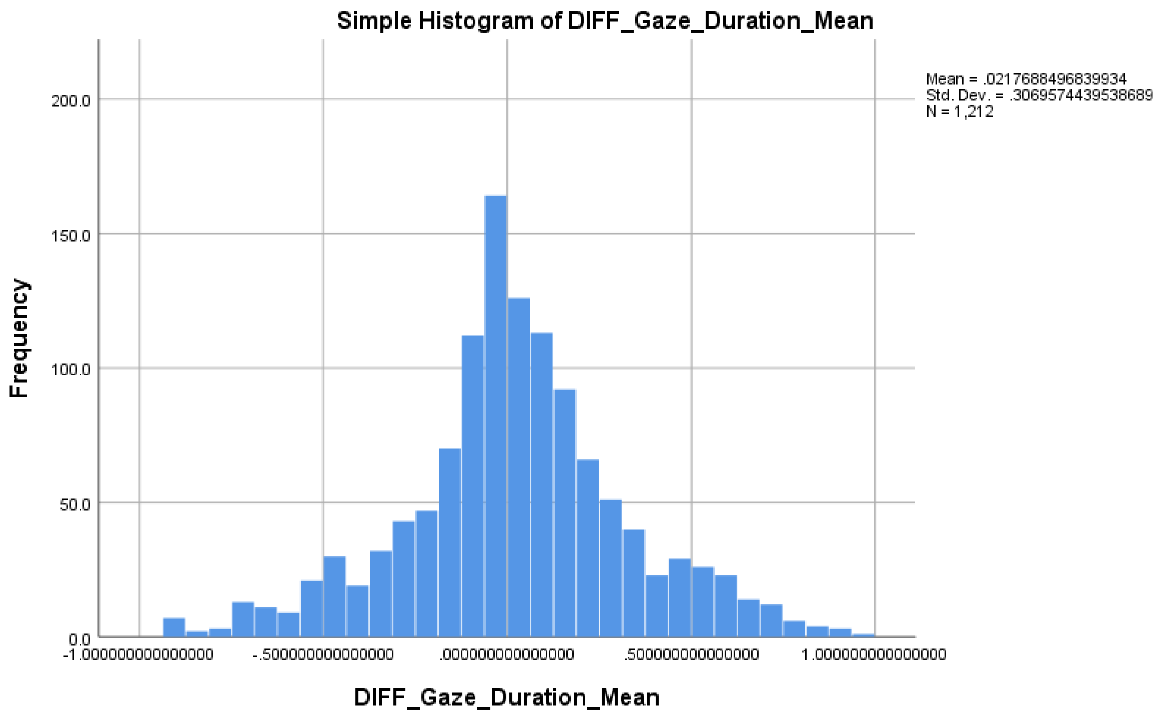

Figure 11. Histogram Distribution of the Gaze Duration Mean Difference Distribution (DIFF_Gaze_Duration_Mean)

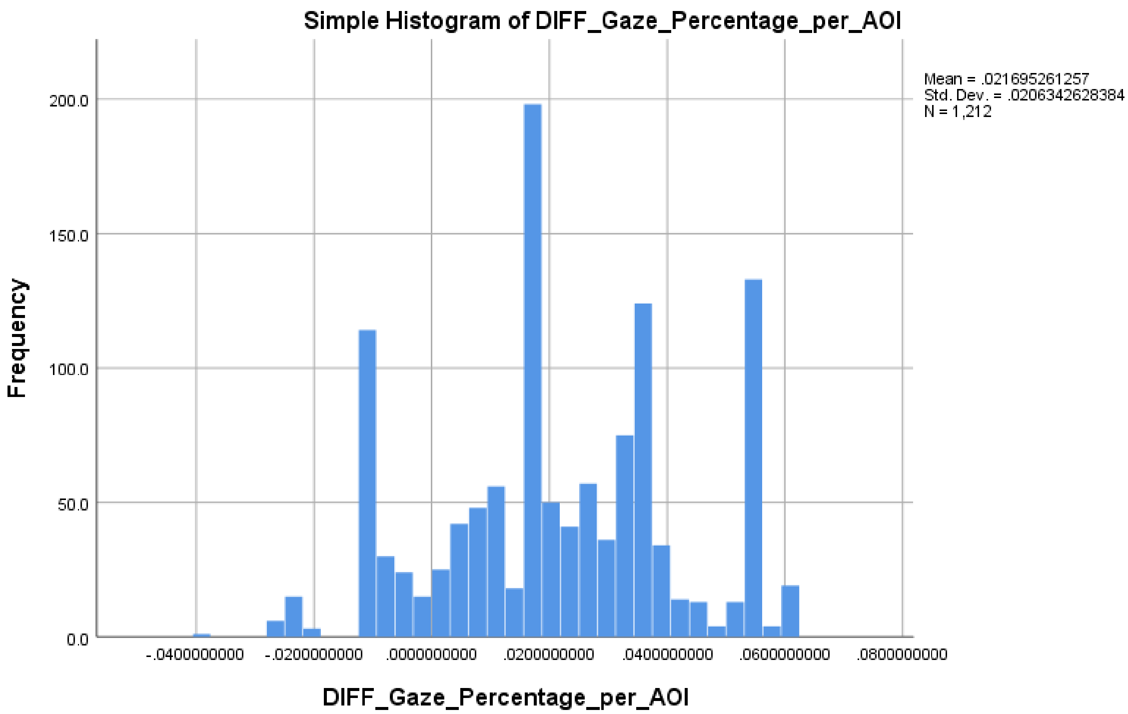

Figure 12. Histogram Distribution of the Gaze Percentage per AOI Difference Distribution (DIFF_Gaze_Percentage_per_AOI)

The normality of the four dependent variable difference distributions were assessed with the Kolmogorov-Smirnov test and the Shapiro-Wilk test. All four residuals for both tests were significant (p<0.5) as can be seen in Table 4, which meant that the difference distribution plots are not normal. One of the assumptions for the paired t-test was found to be invalid.

Table 4

Tests for Normality

Dependent Variable Residual	Kolmogorov-Smirnov[a] Statistic	K-S Df	K-S Sig.	Shapiro -Wilk Statistic	S-W df	S-W Sig.
DIFF_Time_to_ First_Fixation	0.102	1212	0.000	0.967	1212	0.000

Table 4 (Continued)

Tests for Normality

Dependent Variable Residual	Kolmogorov-Smirnov[a] Statistic	K-S Df	K-S Sig.	Shapiro -Wilk Statistic	S-W df	S-W Sig.
DIFF_Fixation_ Frequency_per_AOI	0.233	1212	0.000	0.824	1212	0.000
DIFF_Gaze_ Duration_Mean	0.069	1212	0.000	0.985	1212	0.000
DIFF_Gaze_ Percentage_per_AOI	0.071	1212	0.000	0.971	1212	0.000

a. Lilliefors Significance Correction

Outliers:

Scatterplots for the four dependent variables versus independent variable can be seen in Figures 13, 14, 15 and 16, and all outliers were identified as numbered data points on the plot. The graphs were visually inspected for data points that "lie outside the area of the plot that contains most of the data points (Warner, 2013)." While outliers were identified, none were removed from the distribution before the paired t-test was performed.

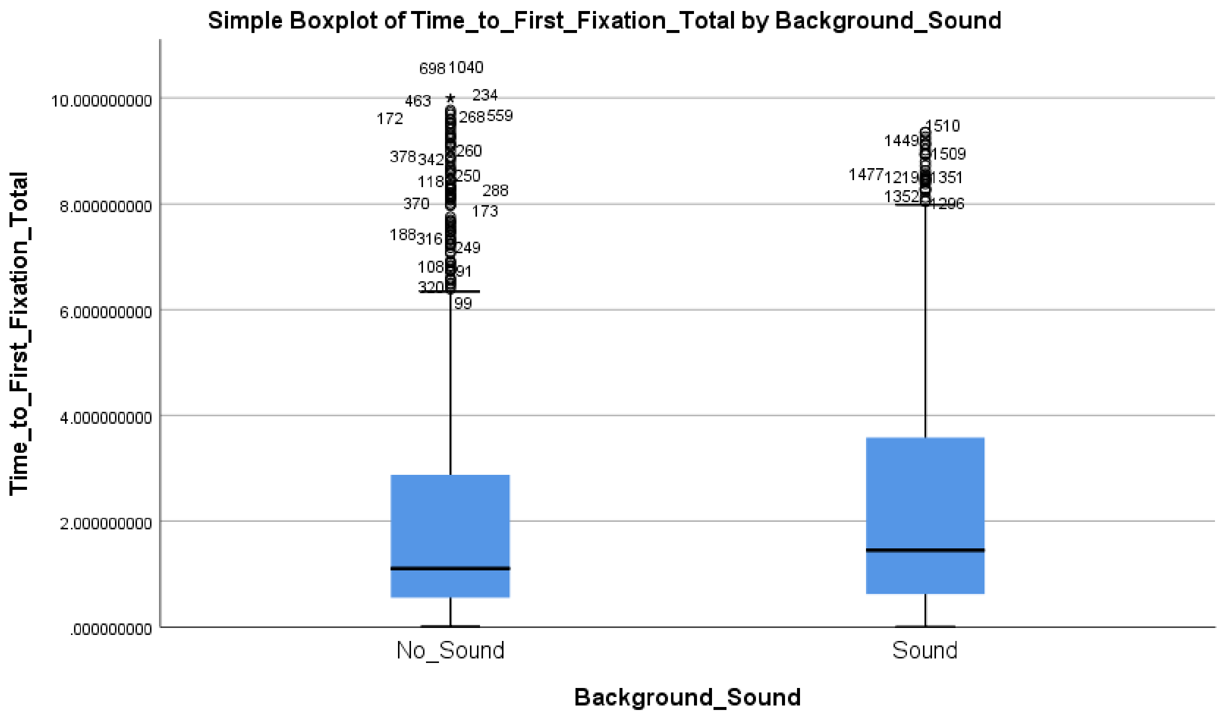

Figure 13. Boxplots of Time to First Fixation

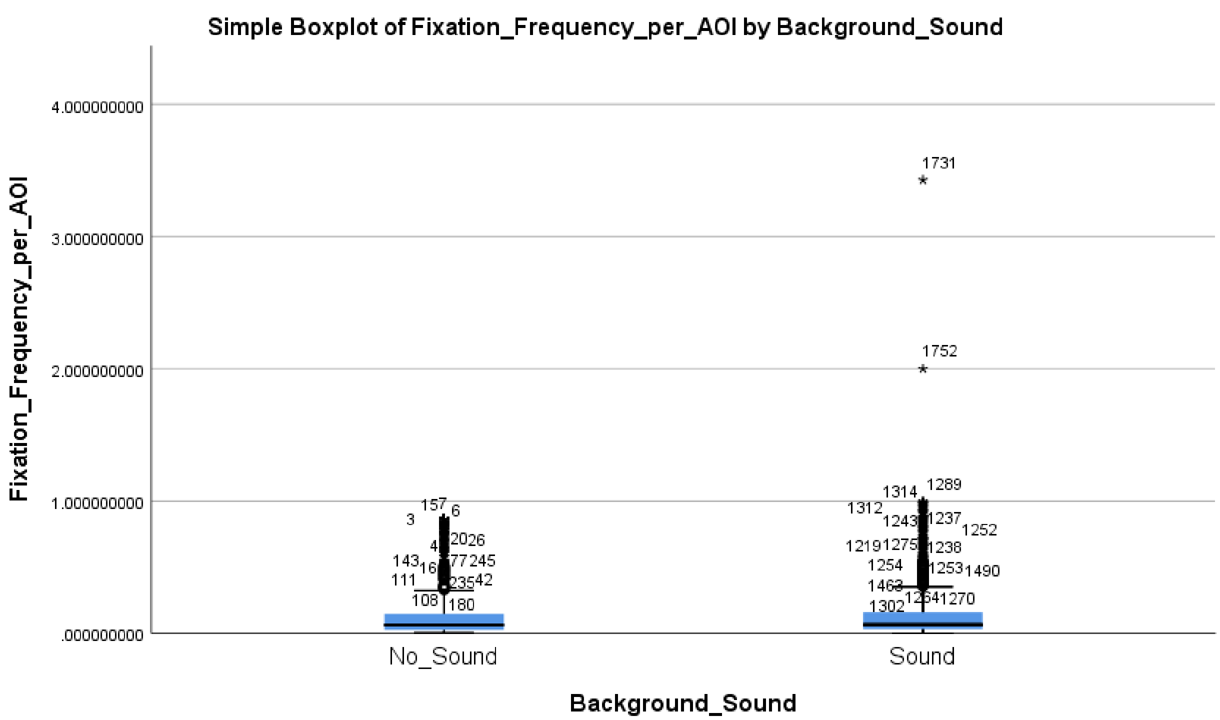

Figure 14. Boxplots of Fixation Frequency per AOI

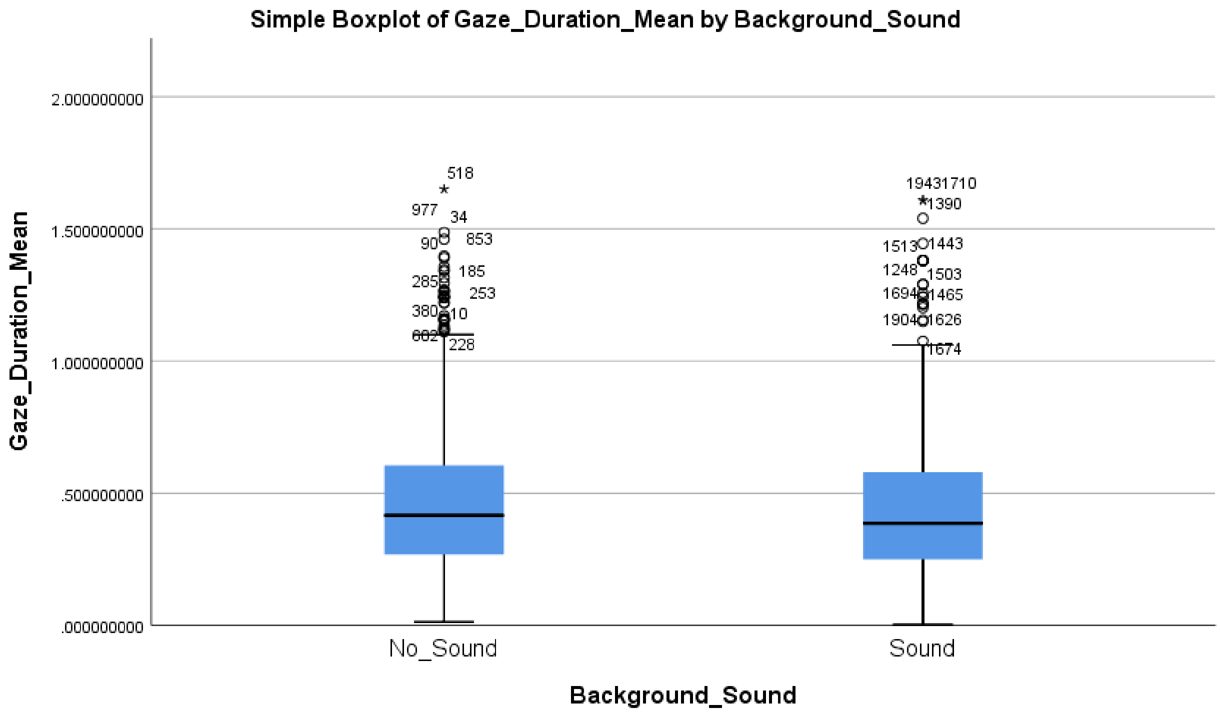

Figure 15. Boxplots of Gaze Duration Mean

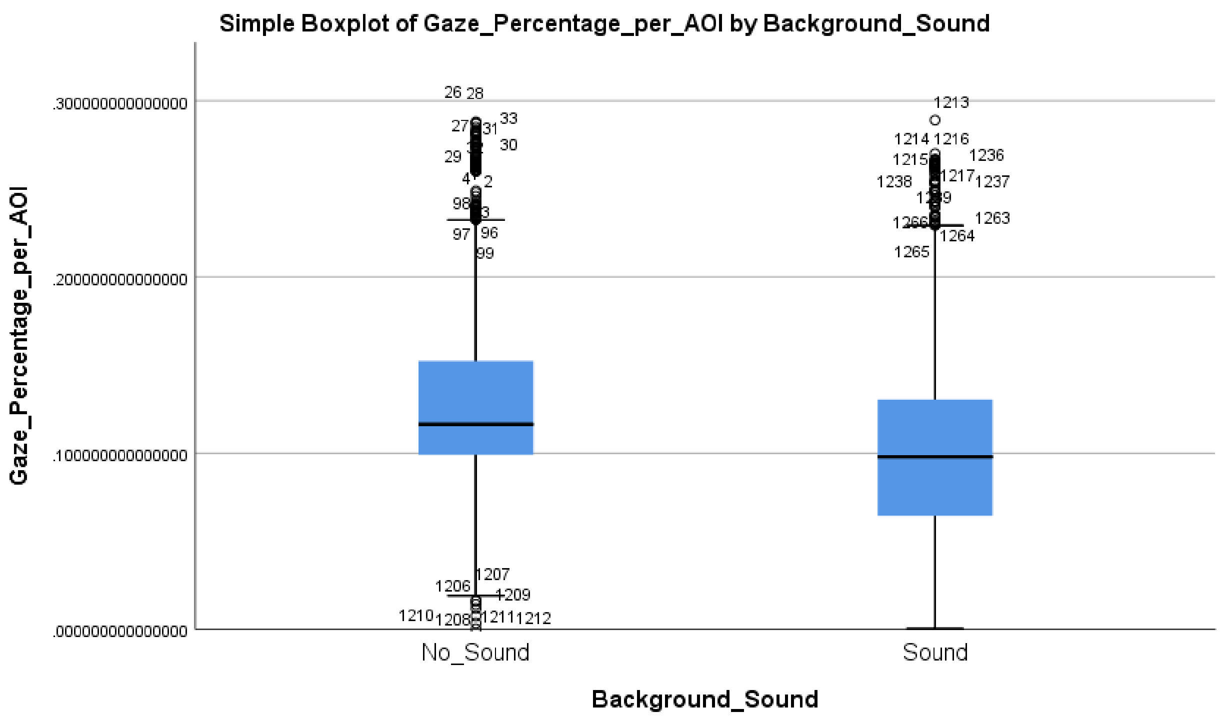

Figure 16. Boxplots of Gaze Percentage per AOI

The regression standard predicted value was plotted against the regression standard residual in a scatterplot (Figure 17, 18, 19 and 20), and the graphs were visually inspected to note the presence of outliers as well as for heteroscedasticity. These plots were approximately straight linear correlations, which demonstrated a minimized risk of heteroscedasticity.

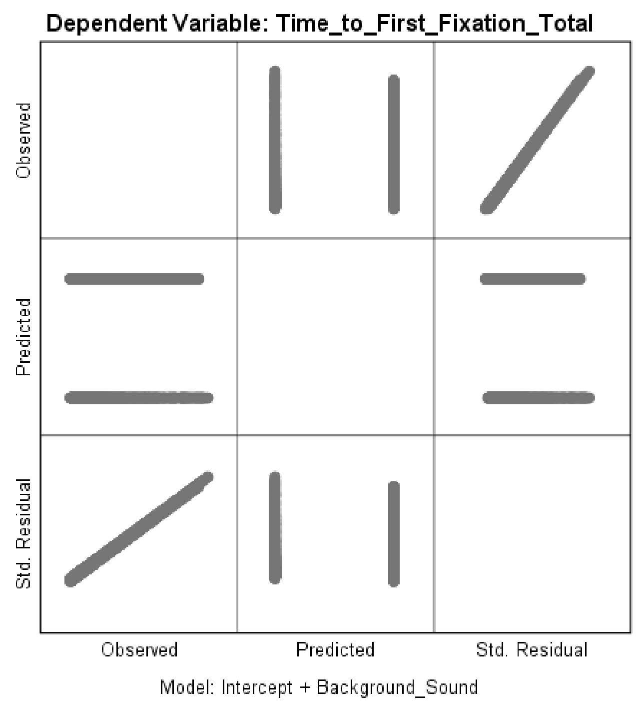

Figure 17. Regression Standard Predicted vs. Residual Plot for Time to First Fixation

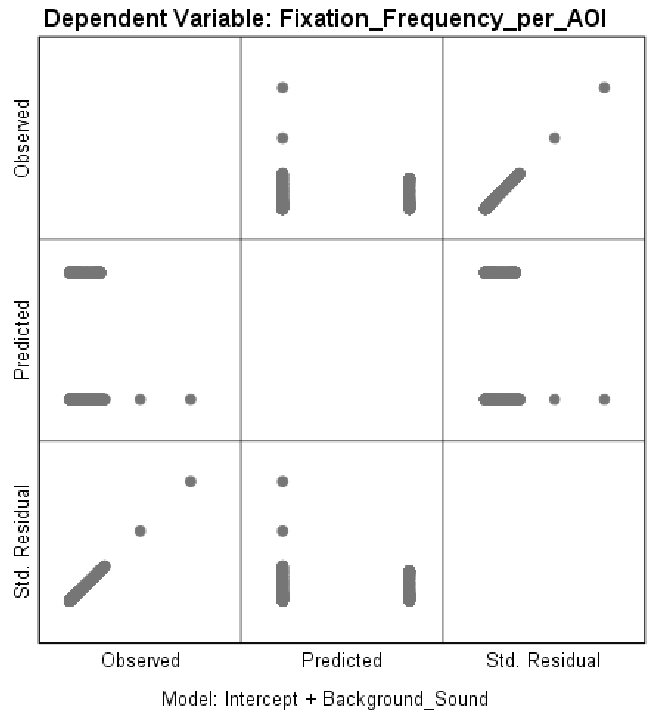

Figure 18. Regression Standard Predicted vs. Residual Plot for Fixation Frequency per AOI

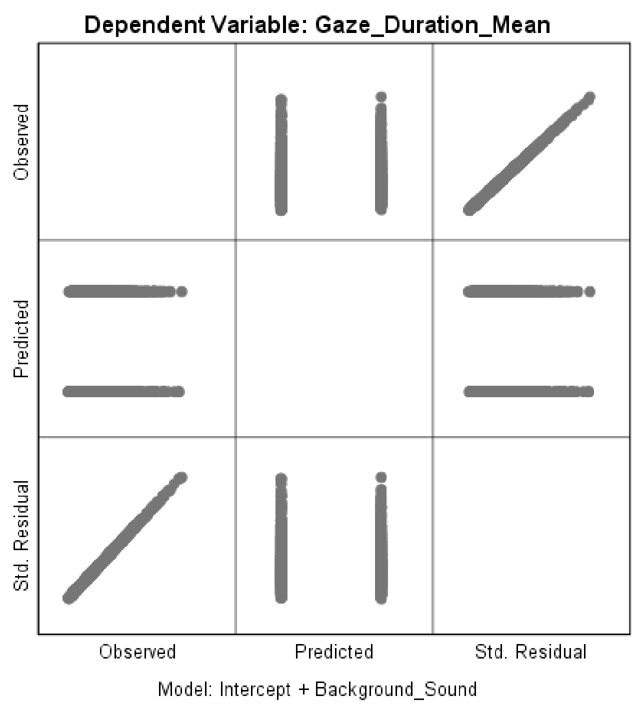

Figure 19. Regression Standard Predicted vs. Residual Plot for Gaze Duration Mean

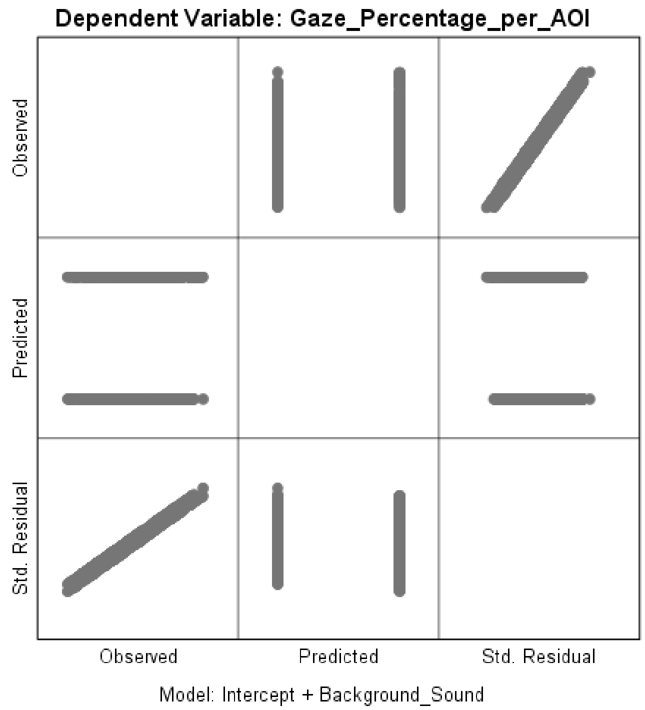

Figure 20. Regression Standard Predicted vs. Residual Plot for Gaze Percentage per AOI

Levene's Test of Equality of Error Variance (based on mean) was performed (Table 5) to note if the variances are equal. The Levene's test was not significant ($p \geq 0.05$) for all four dependent variables; this meant that the variances were considered equal for the two Background Sounds: Ambient Sound and No Ambient Sound sample sets.

Table 5

Levene's Test of Equality Variance (based on mean)[a,b,c,d]

Dependent Variable	Levene Statistic	df1	df2	Sig.
Time_to_First_Fixation_Total	2.716	1	2422	0.099
Fixation_Frequency_per_AOI	1.250	1	2422	0.264
Gaze_Duration_Mean	0.312	1	2422	0.576
Gaze_Percentage_per_AOI	0.782	1	2422	0.377

a. There are no valid cases for Time_to_First_Fixation_Total when Background_Sound = .000. Statistics cannot be computed for this level.
b. There are no valid cases for Fixation_Frequency_per_AOI when Background_Sound = .000. Statistics cannot be computed for this level.
c. There are no valid cases for Gaze_Duration_Mean when Background_Sound = .000. Statistics cannot be computed for this level.
d. There are no valid cases for Gaze_Percentage_per_AOI when Background_Sound = .000. Statistics cannot be computed for this level.

Results

The Paired Samples Statistics can be seen in Table 6; there were no missing lines of data (N=1212 for all dependent variables). For Time to First Fixation and Gaze Percentage per AOI, the mean was higher for Sound. For Fixation Frequency per AOI and Gaze Duration Mean, the mean was higher for No Sound.

Table 6

Paired Samples Statistics

Dependent Variable	Mean	N	Std. Deviation	Std. Error Mean
Pair 1 No Sound _Time_to_First_Fixation_Total	2.117982341	1212	2.269720093	0.065196006
Pair 1 Sound _Time_to_First_Fixation_Total	2.376505167	1212	2.253725117	0.064736562
Pair 2 No Sound _Fixation_Frequency_per_AOI	0.181831936	1212	0.302704947	0.008694972
Pair 2 Sound _Fixation_Frequency_per_AOI	0.167096053	1212	0.254936399	0.007322857
Pair 3 No Sound _Gaze_Duration_Mean	0.460259863	1212	0.26924953	0.007733991
Pair 3 Sound _Gaze_Duration_Mean	0.438491013	1212	0.262267476	0.007533436
Pair 4 No Sound _Gaze_Percentage_per_AOI	0.153400574	1212	0.161169706	0.004629479
Pair 4 Sound _Gaze_Percentage_per_AOI	0.184904908	1212	0.205077258	0.00589069

Since the tested assumptions demonstrated non-normality with equal variances, the Wilconox Rank Sum Test (Table 7) was used instead of the standard paired t-test. The paired t-test would be performed if the data had met the normality and homogeneity assumptions. Warner (2013) defines the test as the following:

> The Wilconox Rank Sum Test is a non-parametric alternative to the independent samples t test. It is used to compare mean ranks for independent samples in situations where the assumptions required for the use of parametric test are violated.

Table 7

Wilconox Rank Sum Test

Statistic	S_Time_to_ First_Fixation_ Total - NS_Time_to_ First_Fixation_ Total	S_Fixation_ Frequency_per_ AOI - NS_Fixation_ Frequency_per_ AOI	S_Gaze_ Duration_Mean - NS_Gaze_ Duration_Mean	S_Gaze_ Percentage_per_ AOI - NS_Gaze_ Percentage_ per_AOI
Z	-3.206[a]	-2.181[b]	-2.674[a]	-25.776[a]
Asymp. Sig. (2-tailed)	0.001	0.029	0.007	0.000

a. Based on positive ranks.
b. Based on negative ranks.

The Wilconox Rank Sum Test (Table 7) was significant for all four dependent variables ($p<0.05$), which meant that there was a significant statistical difference between Time to First Fixation, Fixation Frequency per AOI, Gaze Duration Mean and Gaze Percentage per AOI for the sample sets for Sound versus No_Sound. This also meant that the null hypotheses for all four dependent variables were rejected.

If the difference distribution for paired sample sets had demonstrated a normal distribution, then a paired t-test could have been performed. The results of that paired t-test are shown in Table 8. They are displayed for informational purposes only, since the Wilconox Rank Sum Test has already rejected the four null hypotheses. In Table 8, three of the dependent variables were significant ($p<0.05$), while the Fixation Frequency per AOI was not significant. Again, the results in Table 8 are for informational purposes only and not a measure of the final results.

Table 8

Paired Samples T-Test (Test Run for Information Purposes Only)

Pair	Paired Differences (PD) Mean	PD Std. Dev.	PD Std. Error Mean	PD 95% Confidence Interval of the Difference Lower	PD 95% Confidence Interval of the Difference Upper	t	df	Sig. (2-tail)
Pair 1, Time_to_ First_ Fixation: NS – S	-0.259	3.076	0.088	-0.432	0.085	-2.926	1211	0.003
Pair 2, Fixation_ Frequency_ per_AOI: NS – S	0.001	0.330	0.009	-0.018	0.020	0.114	1211	0.909
Pair 3, Gaze_ Duration_ Mean: NS – S	0.022	0.307	0.009	0.004	0.039	2.469	1211	0.014
Pair 4, Gaze_ Percentage_ per_AOI: NS – S	0.022	0.021	0.001	0.021	0.023	36.604	1211	0.000

Time to First Fixation:

The null hypothesis was rejected in favor of the alternative hypothesis (Table 7): There was a significant statistical difference in the Time to First Fixation between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing

SCADA user interface. As per Table 6, the Time to First Fixation with No Sound was lower (2.12s) than with Sound (2.38s).

Fixation Frequency per AOI:

The null hypothesis was rejected in favor of the alternative hypothesis (Table 7): There was a significant statistical difference in the Fixation Frequency per AOI between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface. As per Table 6, the Fixation Frequency with No Sound was higher (0.182/sec) than with Sound (0.167/sec).

Gaze Duration Mean:

The null hypothesis was rejected in favor of the alternative hypothesis (Table 7): There was a significant statistical difference in the Gaze Duration Mean between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface. As per Table 6, the Gaze Duration Mean with No Sound was higher (0.460s) than with Sound (0.438s).

<u>Gaze Percentage per AOI</u>:

The null hypothesis was rejected in favor of the alternative (Table 7): There was a significant statistical difference in the Gaze Percentage per AOI between no (minimal) ambient noise and ambient noise for users when viewing alerts/warnings on a petrochemical manufacturing SCADA user interface. As per Table 6, the Gaze Percentage per AOI with No sound (15.3%) was lower than with Sound (18.5%). A correlation between the dependent variables was run with the Microsoft Excel Data Analytics functionality; the results can be seen in Table 9. A value close to 1 is considered to have a highly correlated set of data. The correlations between different dependent variables as depicted in Table 9 are less than 0.1, which means there isn't a high correlation between the dependent variables.

Table 9

Correlation Between Dependent Variables

Dependent Variable	Time_to_ First_ Fixation	Fixation_Frequency _per_AOI	Gaze_ Duration_Mean	Gaze_ Percentage_per_AOI
Time_to_ First_ Fixation	1			
Fixation_ Frequency_per_ AOI	-0.0002	1		
Gaze_ Duration_Mean	0.0082	0.0990	1	
Gaze_ Percentage_per _AOI	-0.0109	-0.0290	-0.0458	1

Heat Maps

A heat map was created for Participant 1 for the first SCADA prototype video (Ambient Sound) to demonstrate the areas of focus for the duration of the video (Figure 21). Areas of longer focus were denoted in yellow and red. Comparing it to the heat map for Participant 1 for the second SCADA prototype video (No Ambient Sound) (Figure 22), there didn't appear to be a major noticeable difference in the two heat maps. Figure 22 had several more yellow and red areas of focus than Figure 21. Heat Map comparisons were not a variable in the experiment and are shown for informational purposes only.

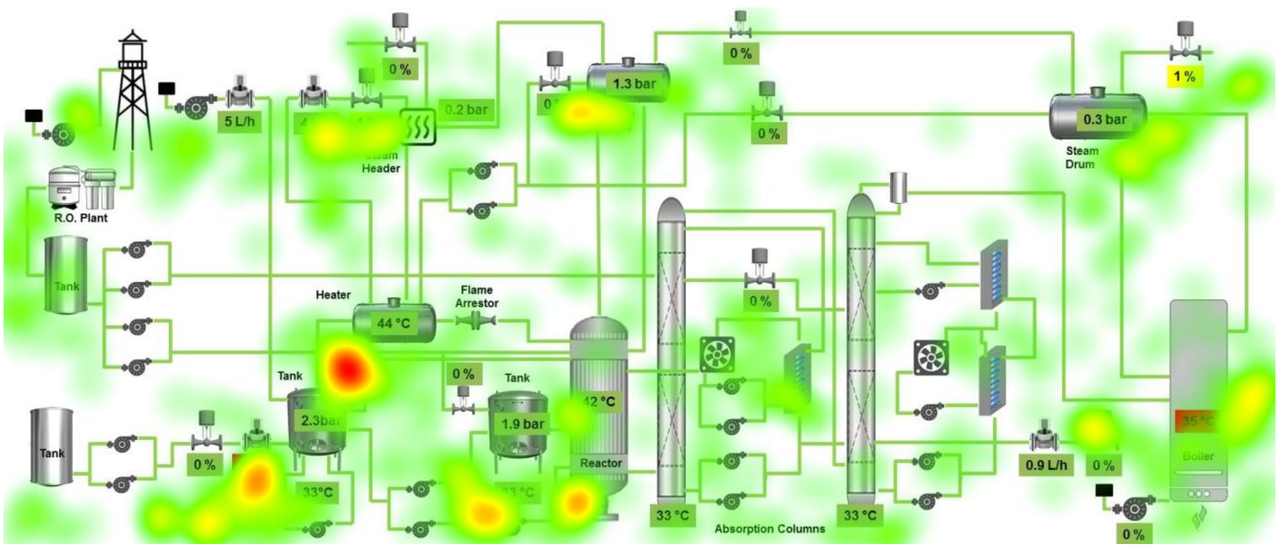

Figure 21. Heat Map for Participant 1 SCADA Prototype Video 1 (Ambient Sound)

Figure 22. Heat Map for Participant 1 SCADA Prototype Video 2 (No Ambient Sound)

Gaze Plots

A gaze plot was created for Participant 1 for the first SCADA prototype video (Ambient Sound) to demonstrate the areas of focus for the duration of the video (Figure 23). Each fixation point was denoted by a circle with a number in it. The first fixation point had a number 1 in a circle, the second had a number 2 in the circle, etc. The diameter of the circle increased as the duration of the fixation at that point increases. Comparing it to the gaze plot for Participant 1 for the second SCADA prototype video (No Ambient Sound) (Figure 24), there didn't appear to be a major noticeable difference in the two heat maps. It was difficult to distinguish a difference in the gaze plots in Figures 23 and 24, but the overall shaping of the clusters appeared very similar between the two gaze plots (i.e. The six black pumps are visible on the left-hand side of the picture in both Figures). Gaze Plot comparisons were not a variable in the experiment and are shown for informational purposes only.

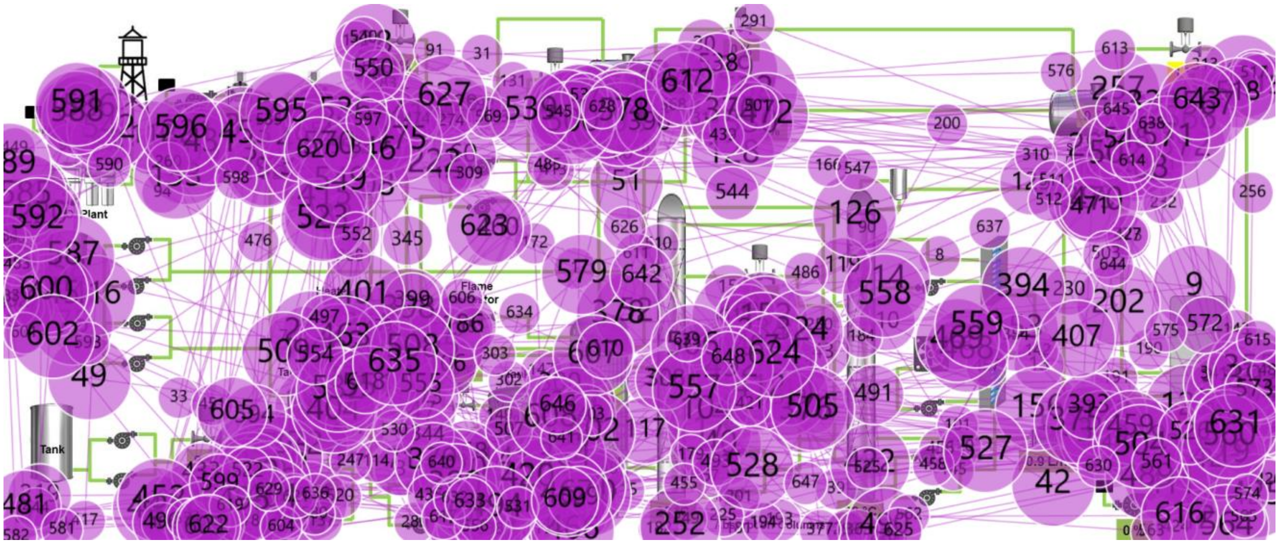

Figure 23. Gaze Plot for Participant 1 SCADA Prototype Video 1 (Ambient Sound)

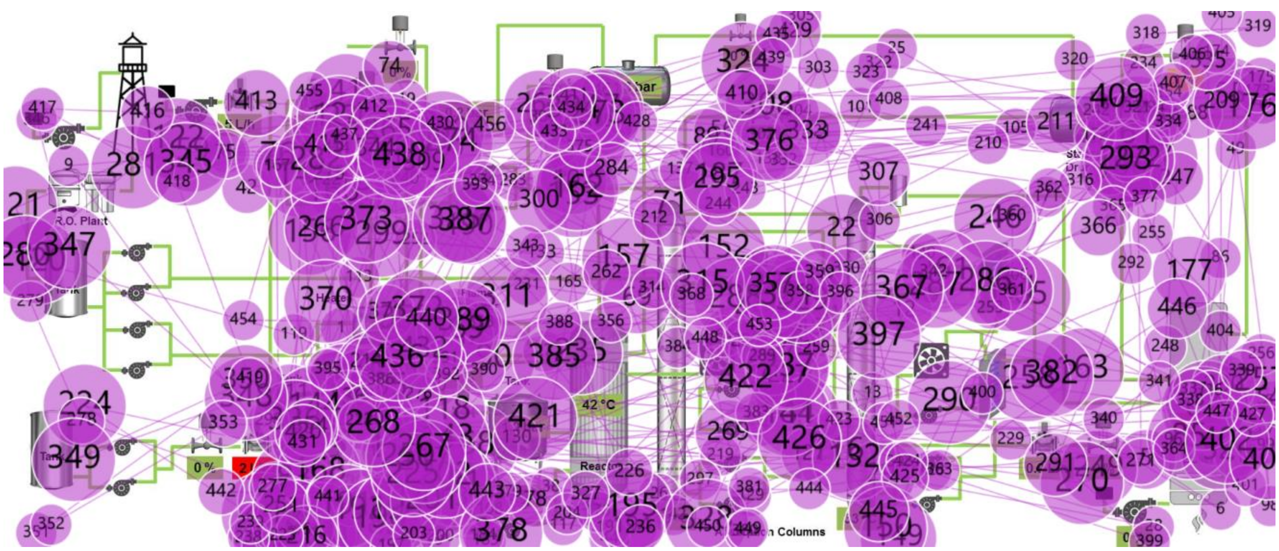

Figure 24. Gaze Plot for Participant 1 SCADA Prototype Video 2 (No Ambient Sound)

CHAPTER 5

CONCLUSIONS

Summary

It was hypothesized that the presence of the ambient background noise would be a distraction to users, and that this would cause any of the following scenarios to occur when ambient sound is present:

1. The Time to First Fixation was longer: It took the participants longer to identify that a warning or alert is occurring.
    a. This was found to be true. The Time to First Fixation was significantly longer when there was ambient sound present (Table 6). It was concluded that the participants were able to focus more on the task of identifying alerts and warnings when there was no sound present, and the ambient sound was a distraction to the participants.
2. The Fixation Frequency per AOI was lower: The participants became distracted and had less eye fixations on the AOIs (warnings and alerts). Their gaze was less prevalent on the AOIs.
    a. This was found to be true. The fixation frequency was significantly lower when there was ambient sound present (Table 6). The participants were less focused on the AOI and became more distracted when there wasn't any

sound present. The findings for Fixation Frequency per AOI were complementary to the conclusions for Time to First Fixation.

3. The Gaze Duration Mean was lower: The participant became distracted and spent less time looking at any one point on the screen. Their gaze wandered quickly from place to place on the screen.
    a. Again, this was found to be true. The Gaze Duration Mean was significantly lower when there was sound present (Table 6). The participants became distracted and spent less time looking at any one point on the screen when sound was present, and their gaze wandered more quickly from place to place on the screen. These results were also aligned with the findings for the previous two metrics: Time to First Fixation and Fixation Frequency per AOI.
4. The Gaze Percentage per AOI was lower: The participant became distracted and didn't spend time looking at the AOIs (warnings and alerts). Their gaze was less prevalent on the AOIs.
    a. This was not found to be true. While the previous three metrics demonstrated that the presence of sound was more distracting to the participants, this metric presented the opposite result. The Gaze Percentage per AOI was significantly higher when there was sound present. The participants became distracted and didn't spend as much time looking at the AOIs when there was no ambient sound; their gaze was less prevalent on the AOI when there was no ambient sound. The findings for this metric were opposed to the conclusions of the previous three metrics: Time to First

Fixation, Fixation Frequency per AOI and Gaze Duration Mean. The reasons for this finding could be that the users had already identified the alert and warning and were moving their gaze to another location on the screen to look for another issue. It could mean that the users were more engaged and alert, because they had identified the issue and were looking in other areas of the screen for subsequent alerts and warnings. This is an area that would benefit from further research.

All four null hypotheses were rejected in favor of the alternative, which showed the significance of how ambient sound affects the eye behavior. It can be concluded that there is a significant difference in viewing the samples in the presence of sound versus no sound. Since three of the four metrics: Time to First Fixation, Fixation Frequency per AOI and Gaze Duration Mean were significant in demonstrating that ambient sound was actually distracting to the participants. This meant that having an environment with the chemical manufacturing noise either caused the users to become distracted over time and not focus, or the lack of sound provided an environment for the participants to be more focused in their task of responding to alerts and warnings. The key metric of Time to First Fixation was significant in identifying that it took longer for participants to respond to alerts and warnings when there was sound present; the fact that two other metrics also aligned with that finding gives further credence to that conclusion. There is a high level of confidence in the data and findings due to the controlled environment and the large number of participants for the study.

Significance of Findings

Since it was identified that the ambient noise caused a distraction to the chemical manufacturing operators while viewing a SCADA screen, it is even more imperative to provide a sound-insulated environment to the SCADA operator, so that they can be more effective in identifying warnings and alerts on the screen. Quick identification of issues in a chemical manufacturing plant can lead to faster mitigation of the problem. Due to the severity of the associated risks in operating a chemical manufacturing plant, this step of finding the process areas that are not running to the appropriate operating specification is very crucial. In this high stress environment, it is in the best interest of the chemical manufacturer to provide optimal conditions for operators to function to the best of their abilities. In this case, identifying that sound causes a distraction is a first step in mitigating the issue.

Recommendations for Further Research

Further research regarding sound distraction and its impact on eye behavior for chemical manufacturing operators is recommended. A further study held in a chemical manufacturing environment with actual chemical manufacturing operators would strengthen the findings of this experiment. In this subsequent study, it would be beneficial to include multiple sites in the study to broaden the depth of research and explore how the visual SCADA representation may affect the results. In further research, the specific sounds of chemical manufacturing sounds could be investigated to see if repetitive sounds cause a distraction or if specific processing sounds (i.e. boiler or pumps) have an impact on the results. It would be beneficial to explore if alert and warning sounds that correspond to the visual alerts and warnings would have an impact on the results.

In regards to the eye tracking variables themselves, there is also further research to perform. If Time to First Fixation is longer, Fixation Frequency per AOI is lower and Gaze Duration Mean is lower when sound is present, then there is a strong indicator that the presence of sound is distracting. The results of the fourth hypothesis are contrary to the findings of the three other metrics. The Gaze Percentage per AOI is significantly higher in the presence of sound, but this is opposed to the findings of the other three metrics. The results of this indicator are not as fundamental to the conclusions as Time to First Fixation would be, since this is the time it takes a participant to respond to an alert or warning. The results are still significant in favor of the lack of sound being distracting (for this one metric). A study investigating the correlation between these four and other eye tracking metrics would be of interest. Another study could investigate if there is any difference in how these four variables result in the presence of other types of environments (besides SCADA chemical manufacturing). Perhaps this metric is not as fundamental to identifying eye behavior as was initially identified; the strength of the relationship between this variable and other eye tracking metrics should be explored further.

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APPENDIX 1: INSTRUCTION AND TRAINING

This session is designed to simulate a real life scenario for an operator in a chemical manufacturing plant. There are three five minute sessions that I will show to you. In between each session, we can take a break for as long as you would like to have before moving to the next session. If at any time you feel uncomfortable during the session, then we can discontinue the testing. Please fill out the demographics form provided.

SCADA is a user interface monitoring system for operators in a chemical manufacturing plant to see the overall status and identify if there are any issues with any of the pieces of equipment in the plant. You can see some of the pieces of equipment in the hypothetical plant like the cooler and the boiler. There are certain values (like temperatures and pressures) that the operators would monitor, and they would be alerted if they see those values go out of a set range that is safe for the function of the chemical manufacturing plant.

I will also be asking you to wear a set of glasses that allows me to track your eye movements as you watch the SCADA screen. Do you feel comfortable wearing them?

In this scenario, you will be monitoring the status of a chemical manufacturing plant. Please just observe the screen as you naturally would, and then at the end of the session, we can talk about what you noticed on the screen.

Do you have any questions or concerns before we get started?

APPENDIX 2: DEMOGRAPHICS FORM

Provide information about yourself; all the information provided will be kept confidential.

If you do not wish to answer a particular question, just leave it blank.

1. Name: _________________________________

2. Age: _____

3. Gender:
   O Male
   O Female

4. Please specify your background:
   O Science
   O Engineering
   O Manufacturing
   O None of the above

5. Please identify your current vision capabilities:
   O Don't wear glasses or contacts - 20/20 vision
   O Wear Contacts that correct vision to 20/20 vision
   Left eye vision without contacts (also note if you have a stigmatism):
   ____
   ____
   Right eye vision without contacts (also note if you have a stigmatism):
   _ ____
   ____
   Are your contacts biofocal or trifocal? O Bifocal O Trifocal O Neither
   O Wear glasses that correct vision to 20/20 vision
   Left eye vision without glasses (also note if you have a stigmatism):
   ____
   ____
   Right eye vision without glasses (also note if you have a stigmatism):
   _ ____

____

O Don’t have 20/20 vision or vision that is corrected to 20/20

6. Please identify if you have any of the following hearing disorders (American Hearing Research Foundation, 2016):

O Acoustic Neuroma
O Autoimmune Inner Ear Disease (AIED)
O Barotrauma
O Cogan’s Patient Story
O Cogan’s Syndrome
O Congenital Deafness
O Excessive Ear Wax
O Gentamicin Toxicity
O Glomus Tumors
O Hearing Loss
O Noise Induced Hearing Loss
O Otosclerosis
` O Ototoxicity From Ear Drops
O Perilymph Fistula
O Sudden Hearing Loss
O Tinnitus
O Other hearing impairment not listed here. Please specify: ____________________
____
O I don’t have a hearing impairment

Participant Selection:

Participants will be excluded from the study if they answer the following on the demographic forms:

- Question 4: None of the Above
- Question 5: Don’t have 20/20 vision
- Question 6: Acoustic Neuroma, Autoimmune Inner Ear Disease (AIED), Barotrauma, Cogan’s Patient Story, Cogan’s Syndrome, Congenital Deafness, Excessive Ear Wax, Gentamicin Toxicity, Glomus Tumors, Hearing Loss, Noise Induced Hearing Loss, Otosclerosis, Ototoxicity From Ear Drops, Perilymph Fistula, Sudden Hearing Loss, Tinnitus, or Other hearing impairment not listed here