The Use of Eye Tracking as a Measure of Situation Awareness in Power System Control Rooms

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***Abstract*—Power systems control rooms are fast-paced, dynamic environments that require operators to maintain awareness of numerous pieces of information. A construct that has been previously used to examine operator ability to process and retain information is situation awareness. It is the process by which information is perceived, comprehended, and then used to project events that may likely occur. It is often measured using observational or self-report methods. In recent times, however, researchers have started using physiological measures such as eye tracking to measure situation awareness. In this paper, we report a pilot study exploring the use of eye tracking metrics to evaluate situation awareness in the operation of a test power system within the confines of a typical control room. Eye tracking results are compared to the results of a Cognitive Task Analysis (CTA), with elaboration of their implications.**

Index Terms: *Cognitive Task Analysis, Eye Tracking, Human Factors, Operators, Power Systems, Situation Awareness.*

I. Introduction

Power system control room operators and engineers work in a fast-paced and dynamic environment. The work they do often require a detailed understanding of the current and future state of numerous facets of the electrical grid [1]. These requirements are heightened during emergency situations (e.g., extreme weather events, electromagnetic disturbances) when processing, understanding, and predicting future states based on extensive amounts of information over brief time frames is required [2]. These are essentially the elements of Situation Awareness (SA) and numerous historical power outages that have been caused, in part, by inadequate operator SA. A prime example of one of these events was the August 14, 2003, east coast power outage. This outage affected more than 50 million people in eight U.S. states and the Province of Ontario and resulted in a cost between four billion and ten billion dollars [3]. In a report to the U.S. President and Canadian Prime Minister following the outage, inadequate SA was directly cited as a contributing factor [4].

Since the 2003 blackout, several papers have been published addressing SA of power system operators [1], [5] that were primarily measured using observational (e.g., query method) or self-report (e.g., questionnaires). The result of these studies was the development of a goal-directed task analysis of transmission operator responsibilities, establishing a baseline measurement of operator SA, and suggesting design principles for power system visualizations to help improve SA [1], [3], [4], [6], [7]. While the information from these studies has been foundational, many of the studies examined SA using freeze probe techniques. Freeze probe techniques (e.g., Situational Awareness Global Assessment Technique (SAGAT)) have been widely validated and allow for an effective measure of SA. However, these techniques require that simulations be stopped to administer queries for measuring SA [8].

Numerous methods have been developed to measure SA in near real-time, not requiring freeze probes. One of the most promising of these methods is eye tracking. It has been previously examined as a means of measuring SA in several studies. Eye tracking metrics, such as number of fixations, fixation duration, and scan path, have all been correlated with overall SA performance measured using both observational & self-report methods [8]-[11]. Additionally, some authors have suggested that different eye tracking metrics may specifically correlate to the different levels of SA used in Endsley's model [11].

The objective of the study presented here was to examine the SA requirements of control room operators and to identify how well eye tracking metrics could be used to inform their SA. Experienced students were used as a proxy for the operators themselves and eye tracking performance measures were recorded. These metrics were then validated by comparing them to an assessment of SA in the form of a cognitive task analysis. Deficiencies in SA were then examined and alterations in the design of visualizations were suggested to improve overall SA.

This paper is organized as follows. Section II highlights the SA model, and Section III presents the experimental procedure, cognitive task analysis (CTA) method and metrics used to assess SA of participants during the operation of a test power system. CTA and eye-tracking results illustrating behavior of participants during the experiments are in Section IV. Finally, Sections V and VI provide further discussion of the results and conclusions.

II. A Brief Overview of SA

A common construct that examines how information is processed and understood over brief timeframes is SA. SA is commonly defined as "the perception of the elements in the

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environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future," or more simply "knowing what's going on" and being able to make a good decision with that information [12], [13].

SA is part of a cyclical decision-making process and is composed of three progressive steps that increase one's awareness of a given situation. Fig. 1 depicts the model that was proposed in [12].

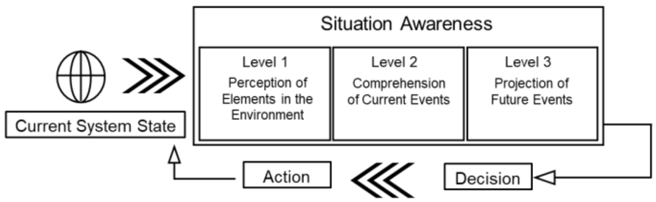

Fig. 1. The SA Model

A. Level 1 SA: Perception

The SA model begins with the perception of elements within one's environment [12]. In a power system control room these elements consist of numerous human-made artifacts including various displays, visualizations, and other pieces of computer hardware and software presented on the Human Machine Interface (HMI). Perception of these elements involve recognizing what they are (e.g., a graph on a computer screen) and determining their characteristics (e.g., color of lines on the graph).

B. Level 2 SA: Comprehension

After someone perceives elements, they begin to comprehend the element's meaning by combining separate but complementary pieces of information. For example, consider the visualization shown in Fig. 2. In this visualization, the flow on a transmission line is surpassing the line's limit. To arrive at this conclusion, an operator must link numerous interrelated observations. These include the color and size of the pie chart over the transmission line and the percentage value within the pie chart. Taken together, these observations inform the operator that this transmission line is overloading.

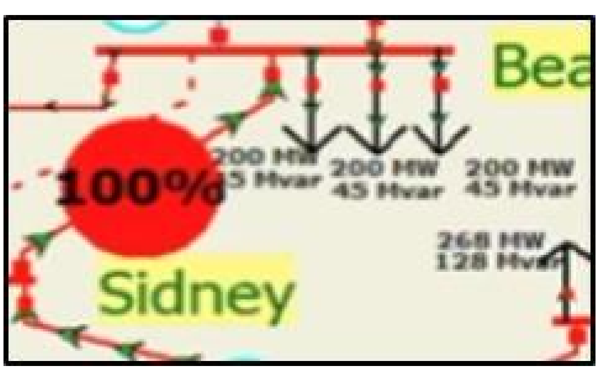

Fig. 2. A Visualization of the Flow on a Transmission Line

C. Level 3 SA: Projection

Once the meaning of an element has been comprehended, the individual can begin to infer what may could occur in the future given the current circumstances. Consider the previous example of an overloading transmission line; upon seeing that the line is in danger of overloading, an operator may realize that increasing generation at the receiving end or decreasing generation at the sending end may be necessary to prevent overloading the line and subsequent disconnection from the grid [5].

III. Methods, Experimental Procedure, and SA Assessment of an Operational Test Power System

The primary goal of this study was to establish and evaluate possible protocols for testing SA using eye tracking for electrical grid control room operators. As a result, the sample size was small (three participants). All data (think aloud protocol and eye tracking) were collected in two separate sessions where each participant had to operate, and then control, a simulated test power system.

A. Participants

There were three power system subject matter experts who were previously familiar with the simulation examined. Two participants were young adult males, and one participant was a young adult female.

B. Power Systems Simulation

The power system simulation examined in this paper was a 42-bus, Illini system [14], and its one-line diagram is shown in Fig. 3.

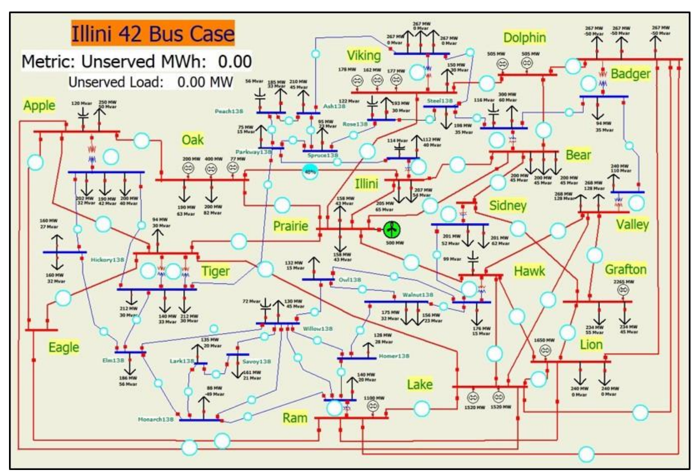

Fig. 3. The 42-Bus Test Power System

The simulation was rendered in a user-interactive, real-time power system simulator [15]. During the simulation, a simulated tornado strike occurs that disconnects three transmission lines. The user's goals during this simulation are the following:

- to prevent the system from collapsing and causing a cascading blackout,

- to disconnect the least amount of load, and

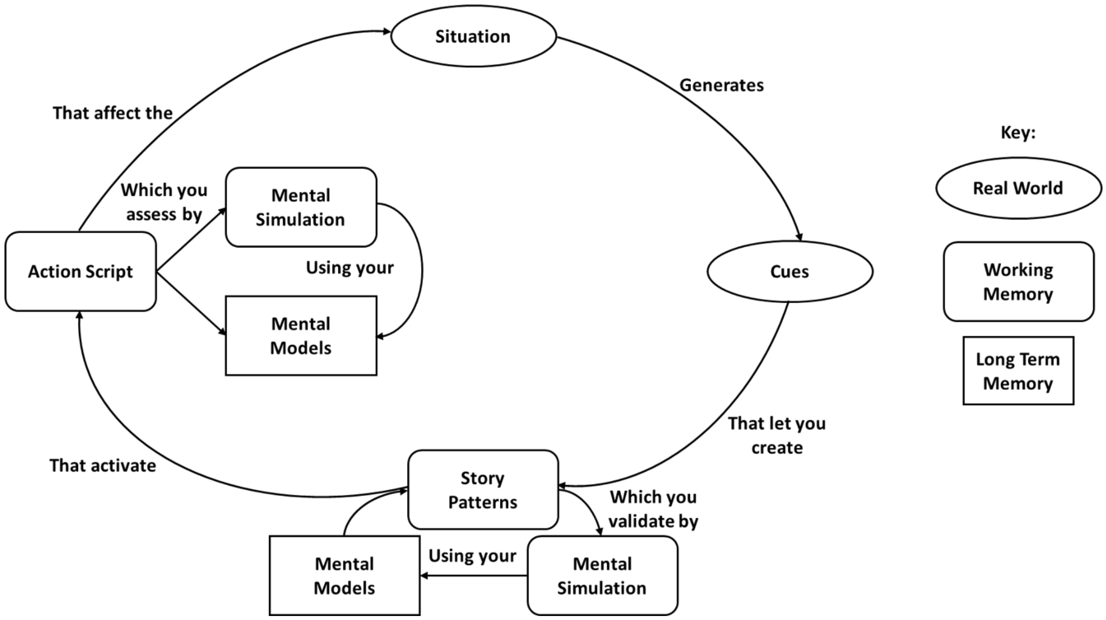

Fig. 4. NDM Guided Cognitive Task Analysis

- to maintain system elements within their operational limits.

C. *Cognitive Task Analysis (CTA)*

CTA was conducted to assess the SA requirements of the users of the power system simulation. This analysis was based on a Naturalistic Decision-Making (NDM) model that was developed in conjunction with the U.S. Department of Energy and has been previously applied to power system settings [4]. This model incorporates SA and sees SA as part of a larger process.

This process starts with the current state of the system, also known as the situation. The situation then generates cues, which are like spheres of understanding. Cues may be generated by alarm logs, charts, or displays, and may represent information such as voltage stability. The more experienced an operator has, the wider their sphere of understanding will be, resulting in the recognition of more cues. Cues are then used to recognize patterns in the information being displayed. These patterns are then used to retrieve relevant mental models from the user's long-term memory. Additionally, patterns can be used to perform mental simulations to check the consistency of the cues being observed. Mental models and simulations then build stories that help increase the operator's SA [5].

As seen in Fig. 4, it is within this portion of the model where Ensley's levels of SA are identified. Specifically, users must activate action scripts with these stories. These action scripts are ways of dealing with a situation that has been stored in user memory. The usefulness of the action scripts is assessed through mental models and simulations, and once these action scripts are put into place, they change the state of the system, causing the cycle to repeat [5].

To develop a CTA based on this model, users were asked to "think aloud" while they were performing the required tasks during the simulation. What they said was transcribed, and the content of that transcription was analyzed, with specific focus on the objects or nouns mentioned by the user. Then the actions the users performed with these objects, the current state of the system, objectives, and cues were identified and coded. With this information, the mental models and levels of SA were established.

D. *Eye Tracking Metrics*

Numerous eye tracking metrics have been previously validated for the measurement of SA. A previous study [8] found that overall SA score, performance, and number of errors were compared to several metrics, including number of fixations, gaze duration, and scan path.

Fixations are a measurement of the eye-in-head position over a particular duration and are typically measured in degrees per second [8]. A larger number of fixations may indicate less efficient searching by users, while an increased fixation duration may be indicative of difficulty extracting information.

Gaze duration is the duration and spatial location of a series of fixations [8]. Gaze duration is relevant to SA because the proportion of time spent looking at a display element could indicate the importance of that element.

Scan path is the spatial arrangement of a series of fixations [8]. Scan path may indicate how users are attempting to locate information on a display, as well as the ease in which users can extract that information.

E. Experimental Procedure

The CTA was conducted, and eye tracking data was gathered to determine the SA requirements and level of SA displayed by the participants. The data for the CTA and the SA were gathered on two separate occasions with the participants.

During the first occasion, due to COVID 19 protocol limitations, participants connected with the experimenter via video conference and completed three rounds of the simulation. The video conference for each round was recorded and transcripts were generated for use in the CTA. During this first instance, no eye tracking was utilized.

During the second occasion, data were also gathered via video conference and transcripts were generated for use in the CTA. However, on this instance, eye tracking data was also gathered by utilizing the *Argus Science ETVision* eye tracking system [16]. After data collection was finished, a CTA was completed, and eye tracking data was analyzed with *iMotions* software [17].

F. Analyses

Given that the objective of this pilot study was to examine the SA requirements of control room operators and to identify how well eye tracking metrics could be used to inform their SA the following analyses were conducted. Eye tracking metrics were validated by comparing them to SA needs assessment developed by a CTA. Deficiencies in SA were then identified and alterations in the design of visualizations were suggested to improve overall SA.

IV. Results

Multiple runs of real-time, user-interactive simulation of the test 42-bus system were carried out amid the tornado event for each of the participants. During the duration of each simulation, the participant was assessed for their behavior and choice of control actions which they envisioned would preserve the integrity of the system. The assessment methods included the think-aloud method needed for a CTA, and the use of an eye tracker to monitor eye movement during the simulation.

A. Results from Cognitive Task Analysis (CTA)

The CTA identified the following:

- Sixteen unique objects (shown in Table I) with the most frequently mentioned objects being loads, transmission lines, flows, and generators.
- Twenty-six unique actions (shown in Table II) with the most frequently mentioned actions being disconnecting loads, identifying the magnitude of flow on a line, and adding or removing generation.
- Fifteen unique mental models (shown in Table III) primarily concerned with the effects of generation and load on flows through a transmission line.

This result corroborates previous studies [5] and illustrates the large number of objects, actions, and mental models necessary for even a limited portion of the control room operator's job.

TABLE I. UNIQUE OBJECTS

Bus	Bus Frequency Chart	Bus Voltage Chart
Display	Frequency	Generation*
Generator*	Load that is drawing power*	Logs
Logs window	Power setpoint	Real power
System flow*	Transmission line*	Transmission line pie charts*
Voltage		

*Most frequently mentioned

TABLE II. UNIQUE ACTIONS

Change output of flow	Check for anomaly	Decrease real power
Determine bus frequency	Determine direction of flow	Determine generation distribution
Determine maximum output	Determine meaning of buses	Determine meaning of chart
Determine meaning of logs	Determine meaning of window	Determine transmission line state
Disconnect load*	Drop generators*	Drop loads
Familiarize self with display	Identify magnitude of flow*	Identify magnitude of generation
Identify system wide flow	Increase real power	Locate bus
Locate generator & load	Observe chart windows	Read logs
Reduce flow	Reduce generation*	

*Most frequently mentioned

TABLE III. UNIQUE MENTAL MODELS

A flat line on the bus voltage chart means that voltages are stabilizing	Acceptable bus frequency values	Acceptable bus voltage values
Disconnecting loads means depriving customers of power	Flow on the line can be reduced by adjusting generation	Generators are dropped when there is too much flow on a line
Symbology for a bus	Symbology for a dropped generation	Symbology for a generator
Symbology for an open line	Symbology for a transformer	Symbology for flow direction
The flow on the line can be reduced by removing loads drawing power	The frequency can be decreased by decreasing real power	Types of information displayed on logs window

B. Eye Tracking Results

Several distinct findings from the eye-tracking analyses revealed fixations were not evenly distributed across the simulation display. One portion of the screen in which there was a high frequency of fixations was the region (A) surrounding the voltage and power setpoint control segments in the generator information dialogue box as shown in Fig. 5. This portion of the display allows users to perform control actions (that is, increase or decrease megawatt (MW) power output or issue a new voltage setpoint for a selected generator).

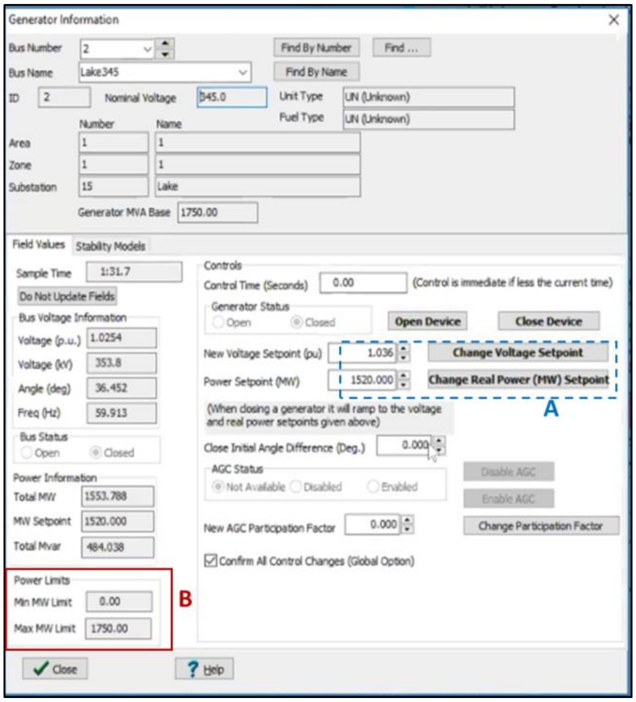

Fig. 5. The Generator Information Dialog. Region A (blue dotted line) had a higher frequency and duration of fixations than Region B (red solid line).

Two important elements within this information box are the power set point and power limits of a generator. The power set point is the targeted MW output, while the power limits, as shown in the region B, are the maximum and minimum MW outputs capable of being produced by a generator. As shown by the heatmap in Fig. 6, it was noted that users had larger number of fixations and a longer fixation duration in region A where users had the ability to input generator control actions (~38 fixations, total dwell time of ~16.8 seconds) compared to region B showing the generator power limits (~12 fixations, total dwell time ~3.6 seconds). Here, the generator information dialog box is at the screen center when a user double clicked on a generator icon on the one-line diagram.

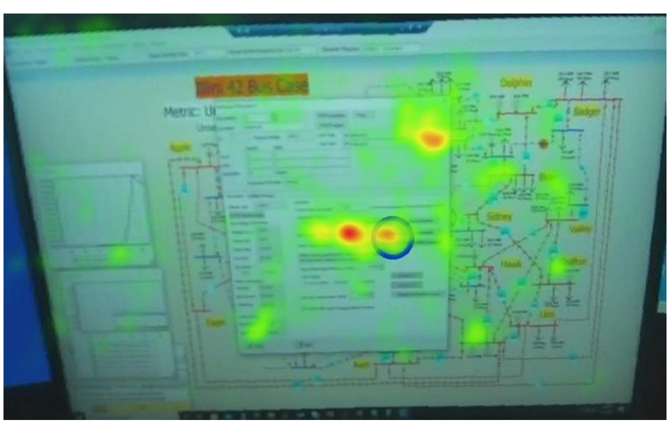

Fig. 6. Generated Heatmap Following User Experiment. The blue circle is the current point of fixation. The red indicates higher fixation duration.

V. Discussion

The goal of this pilot study was to establish and evaluate methods for testing SA using eye tracking for electrical grid control rooms. The results show the value of both the CTA and eye tracking, providing insight into the users' experience and needs. Firstly, the task analysis was able to extract key facets of the tasks conducted by users during the simulation. Many of the objects identified are involved in tasks frequently associated with maintaining power system functioning. For example, a user may control the flow on a transmission line by adding or removing generation or disconnecting loads.

On one hand, CTA's most frequently mentioned unique objects are associated with electrical grid interconnection (flows & transmission lines) from producers (generators) to consumers (loads) whilst the most frequently mentioned unique actions are associated with management of the grid based on established patterns. These actions are patterns required to avoid power interruption from generators (adding/removing generation) through transmission lines (magnitude of flow) to consumers (disconnecting loads).

On the other hand, eye tracking results show participant fixation on generators, a frequently mentioned unique object from the CTA. Their comprehension of the network operation contributed to their concentrating on generator management (Fig. 5), a frequently mentioned unique action from the CTA.

User interactions were further understood when eye tracking data was used in conjunction with the analysis. These data suggested that deficiencies may be present in the simulation that may hinder user SA. These deficiencies are like the SA demons described by Endsley [18]. SA demons can be described as difficulties that occur when aspects of a system's design interfere with a human's ability to process information correctly. These difficulties may result in user inability to develop or maintain SA. The four SA demons noticed during the simulation were misplaced salience, data overload, errant mental models, and attentional narrowing.

Misplaced salience occurs when users become more sensitive to some stimuli over others, such as bright colors and loud noises. Usage of these types of stimuli can either help or hinder SA [18]. An example observed during the simulation occurred when users attempted to add generation to a transmission line. A generator information screen appeared. This screen contained an area for the power set point at the center, or the requested amount of generation a user would like to add. The power set point overshadowed the section of the screen that was related to generator power limits. Users frequently appeared to spend more time fixating on the power set point rather than the generator power limits, which often resulted in users requesting the generator to output more power than it was capable of. As a result, no additional power was generated.

Data overload is a result of user 's inability to process large amounts of data simultaneously [18]. Users verbally implied that they were experiencing data overload by expressing feelings that the simulation was going too quickly, and they felt stressed for time. Users also frequently paused to collect their thoughts and expressed feelings of confusion at some points in the simulation.

The use of errant mental models occurs when users have difficulty connecting disparate pieces of information to form a conclusion [18]. During the simulation, it was observed that users often failed to recognize alternative methods of regulating system flow. If users frequently dropped loads or adjusted generation, they were encouraged to continue with their preferred methods of regulating system flow.

Attentional narrowing occurs when users are unable to divide attention between multiple aspects of a simulation. It was observed during the simulation that users primarily focused on the generator power set point rather than the generator power limits. This attentional narrowing is likely the result of the previously mentioned misplaced salience.

VI. Conclusions

In summary, the most frequently mentioned unique actions by the participants, correlated with their comprehension of the most frequently mentioned unique actions. These patterns were, in turn associated with relevant mental models based for projecting potential consequences of inadequate power management within the network. However, data from the eye tracking suggest that the simulation may need be altered to improve user SA.

One way to accomplish this would be to minimize SA demons. For instance, power setpoint and power limits on Fig. 5 can be consolidated to a percentage representation with a plus (+) or minus (-) button to facilitate generation adjustments based on observed cues. This would minimize fixation on irrelevant portions of the display, enhance understanding and ability to project the results of their actions into the near future, thereby improving their level three SA.

In addition to the findings regarding the task analysis and the eye tracking, analysis of user transcripts revealed numerous difficulties during the simulation. Firstly, participants repeatedly expressed feeling short on time. Additionally, participants often had to pause to collect their thoughts and they expressed feelings of confusion at certain points in the simulation. Finally, participants frequently exhibited difficulty when trying to connect disparate pieces of information, such as when deciding to drop a load or adjust generation to reduce flow on a transmission line.

Another means to improve user SA would be to eliminate the SA demons present within the simulation. This may be accomplished by increasing the salience of the power limits portion of the generator information box (e.g., increasing the size or changing the color). This could also be accomplished by having a warning pop up box appear if the power set point is greater than the maximum output a generator can produce. In addition to these findings, examination of this simulation has demonstrated the value that eye tracking can have when analyzing user SA. This examination has also suggested that eye tracking and CTA can be used in conjunction to gain levels of granularity that neither method is capable of producing independently.

VII. Acknowledgment

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References

[1] M. M. Lenox, E. S. Connors, and M. R. Endsley, "A baseline evaluation of situation awareness for electric power system operation supervisors," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 2011, vol. 55, no. 1: SAGE Publications Sage CA: Los Angeles, CA, pp. 2044-2048.

[2] T. Overbye, R. Klump, and S. Dutta, "Technology Assessment of Power System Visualization (1017795)," 2009. [Online]. Available: https://www.epri.com/research/products/000000000001017795

[3] E. S. Connors, M. R. Endsley, and L. Jones, "Situation awareness in the power transmission and distribution industry," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 2007, vol. 51, no. 4: SAGE Publications Sage CA: Los Angeles, CA, pp. 215-219.

[4] A. Muir and J. Lopatto, "Final report on the August 14, 2003 blackout in the United States and Canada: causes and recommendations," 2004.

[5] F. L. Greitzer and R. Podmore, "Naturalistic decision making in power grid operations: Implications for dispatcher training and usability testing," Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2008.

[6] E. Connors, R. Green, and M. Endsley, "Guidelines for Human-Centered Situational Awareness (1024610)," 2011. [Online]. Available: https://www.epri.com/research/products/000000000001024610

[7] M. Endsley, "Situation Awareness in Power Systems Operations: Guidelines and Recommendations for Supporting Situation Awareness," EPRI, Palo Alto, CA, 2008.

[8] K. S. Moore, "Comparison of eye movement data to direct measures of situation awareness for development of a novel measurement technique in dynamic, uncontrolled test environments," Clemson University, 2009.

[9] E. M. Argyle, J. J. Gourley, Z. Kang, and R. L. Shehab, "Investigating the relationship between eye movements and situation awareness in weather forecasting," *Applied ergonomics,* vol. 85, p. 103071, 2020.

[10] J. C. de Winter, Y. B. Eisma, C. Cabrall, P. A. Hancock, and N. A. Stanton, "Situation awareness based on eye movements in relation to the task environment," *Cognition, Technology & Work,* vol. 21, no. 1, pp. 99-111, 2019.

[11] K. van de Merwe, H. van Dijk, and R. Zon, "Eye movements as an indicator of situation awareness in a flight simulator experiment," *The International Journal of Aviation Psychology,* vol. 22, no. 1, pp. 78-95, 2012.

[12] M. R. Endsley, "Toward a theory of situation awareness in dynamic systems," *Human factors,* vol. 37, no. 1, pp. 32-64, 1995.

[13] C. D. Wickens, "Situation awareness: Review of Mica Endsley's 1995 articles on situation awareness theory and measurement," *Human factors,* vol. 50, no. 3, pp. 397-403, 2008.

[14] TAMU Electric Grid Test Case Repository [Online] Available: https://electricgrids.engr.tamu.edu/electric-grid-test-cases/

[15] PowerWorld. PowerWorld Simulator [Online] Available: https://www.powerworld.com/products/simulator/overview

[16] ETVision System - Eye Tracking System [Online] Available: http://www.argusscience.com/ETVision.html

[17] iMotions Software [Online] Available: https://imotions.com/platform/

[18] M. R. Endsley, B. Bolte, and D. G. Jones, *Designing for situation awareness: An approach to user-centered design*. CRC press, 2003.