ISSN 2616-7433 Vol. 6, Issue 7: 35-39, DOI: 10.25236/FSST.2024.060706

Physiological Monitoring of Situational Awareness

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Abstract: *This article examines the concept of Situation Awareness (SA) and its crucial role in high-risk environments. SA involves the capacity to perceive, comprehend, and anticipate the conditions of various elements within the environment. The paper elaborates on three aspects of SA: perception of environmental elements, comprehension of situations, and prediction of future states. It highlights that individuals with proficient SA can not only capture pertinent information but also synthesize it to foresee potential outcomes. Additionally, the article addresses the challenges in quantifying SA, typically using direct measures and methods that assess SA through analysis of operator actions or performance. It also discusses several physiological metrics, such as heart rate, electroencephalography (EEG), eye-tracking, and pupillary response, which can serve as indirect indicators of an individual's situational awareness.*

Keywords: *Situational Awareness, Physiological indicators, measurement*

1. Introduction

Situation awareness (SA) refers to the capability to understand the elements of an environment, noting their evolution over time or in response to external factors. This concept is crucial for making well-informed decisions in a variety of contexts. Formally, SA comprises three primary components: identifying environmental elements within a given time and space, interpreting their importance, and forecasting their future state [1]. Alternatively, situation awareness can be viewed as an adaptable, outward-oriented cognitive state that fosters comprehension of a shifting operational landscape, thereby directing appropriate actions within that setting. This perspective underscores the dynamic and intentional attributes of situation awareness, emphasizing its influence in adapting to and managing an evolving environment [2].

Situation awareness is recognized as a crucial foundation for informed decision-making across numerous sectors, especially where human life and assets are at risk. It is vital in fields such as law enforcement, aviation, air traffic control, ship navigation [3], healthcare [4], emergency response, military operations, and the management of power grids, self-defense, and offshore oil and nuclear power plants [5]. In these environments, the concept plays a key role in promoting safety, efficiency, and effectiveness amid complex and high-stakes situations.

Poor situational understanding is often identified as a crucial factor in incidents attributed to human errors. Endsley's model of situation awareness highlights the necessity for appropriate and precise decision-making in hazardous conditions, involving key cognitive tasks:

1) Pattern Recognition: Matching elements of the current scenario with known patterns to comprehend the situation.

2) Mental Model Formation: Constructing complex frameworks essential for interpreting environmental dynamics.

3) Knowledge Acquisition: Gaining in-depth and relevant knowledge that informs and enhances decision-making, leading to precise outcomes.

Endsley's theory stresses the significance of these cognitive functions in safely managing dangerous situations.

The study of situational awareness focuses on three principal components: the states, the systems supporting them, and the processes that manage situational awareness.

1) SA States: These represent the level of awareness and comprehension of the surroundings and prevailing circumstances.

ISSN 2616-7433 Vol. 6, Issue 7: 35-39, DOI: 10.25236/FSST.2024.060706

2) SA Systems: These include technological developments specifically aimed at boosting situational awareness in various environments.

3) SA Processes: These involve the methods for evaluating and refining SA states and address factors influencing the continuous enhancement of one's awareness.

Collectively, these elements form a comprehensive framework for understanding, developing, and sustaining effective situational awareness [6].

Despite extensive examination, the concept of situation awareness (SA) presents significant challenges in quantification and assessment due to its complex nature. Typically, SA is measured using Direct Measurement Techniques or Inferred Measurement Methods. Direct Measurement Techniques encompass both objective, real-time monitoring tools and subjective self-report questionnaires that gauge an individual's perceived SA level. These are often considered "product-oriented" because they assess the outcome of the SA process. On the other hand, Inferred Measurement Methods estimate SA levels through the observation and analysis of an operator's behavior and performance outcomes. Known as "process-oriented," these methods focus on the cognitive processes and mechanisms essential for developing SA.

The distinction between direct and inferred measurement techniques highlights the necessity of examining both the results of situation awareness (SA) and the processes that facilitate its development. Emphasizing these aspects is crucial for comprehensively understanding and assessing SA in practical applications.

Situational Awareness (SA) is measured directly by assessing an individual’s consciousness of their surroundings, either through real-time monitoring or self-reported perceptions. Alternatively, indirect methods infer SA by evaluating the underlying processes that shape it, analyzing behaviors and performance to estimate awareness levels. Understanding the differences between these approaches is essential for grasping SA's complexities and its implications across various fields. This dual perspective enables a comprehensive evaluation of an individual's awareness and the contributing factors, enhancing the understanding of SA's role in reducing errors and improving safety and decision-making across diverse domains.

Research indicates that insufficient SA is a significant factor in accidents and errors in sectors like aviation, healthcare, and industrial operations [7][8][9][10]. According to Endsley’s theory of situational awareness, effective decision-making in critical situations relies on recognizing patterns, forming sophisticated schemas, and accessing archetypal knowledge [11]. Losses in SA can precipitate severe outcomes, such as aviation incidents, where a pilot once narrowly escaped disaster due to an automatic system's intervention during a coma induced by high G-forces. Similarly, healthcare professionals might delay treatment or make poor decisions if they lack awareness of a patient’s changing condition, potentially compromising safety. In industrial settings, operators who fail to notice shifts in equipment status or environmental conditions can cause operational mistakes, leading to equipment damage and accidents. On the roads, drivers unaware of their surroundings are at higher risk of causing collisions. Furthermore, first responders and military personnel without adequate SA may make tactical errors or delay actions, reducing the effectiveness and safety of their operations. In nuclear facilities, operators’ failure to correctly assess reactor status could heighten the risk of a nuclear incident.

Monitoring physiological indicators is a key method for assessing situational awareness, encompassing the evaluation of an individual’s physical state in various contexts such as work stress, cognitive load, and safety-related environmental factors. This approach offers an objective assessment of the situational awareness of individuals or teams. Widely utilized techniques include monitoring heart rate, electrical skin activity (EDA), electroencephalography (EEG), and blood pressure, as well as analyzing eye tracking, facial expressions, and pupillary responses.

2. Objective measures

Objective measures accurately assess situational awareness (SA) by contrasting an individual's perceptions with the actual conditions, known as "ground truth." These measures involve collecting data on a person's understanding of a situation and evaluating it against the real events to gauge the precision of their SA at that specific moment. This method allows for a direct measurement of SA without relying on incomplete information from operators or observers. Data collection can occur through one of three methods: in real time, such as through "real-time probes" that pose open questions during task execution; during a pause in task activities, using tools like the Situation Awareness Global Assessment (SAGAT)

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or the WOMBAT Situational Awareness and Stress Tolerance Test, a popular assessment in aviation since the late 1980s also known in Europe as HUPEX; or post-task completion.

3. Subjective measures

Subjective measures assess situation awareness (SA) by having individuals rate either their own SA or that of others using an anchored scale, such as the participant situation awareness questionnaire or the situation awareness rating technique. These measures are appealing due to their simplicity and ease of administration. However, they have limitations, including the potential lack of awareness by individuals of information they are missing. Subjective assessments tend to provide a broad overview rather than exploiting the nuanced, multivariate aspects of SA that objective measures can detail. Nevertheless, self-assessments can offer valuable insights into an operator's confidence in their performance and their auditor's reliability. Moreover, understanding how operators perceive their own SA is crucial, as misperceptions—whether overconfidence or undue skepticism—can significantly impact decision-making at both individual and team levels.

4. Heart rate detection

Heart rate recovery (HRR) is a conventional physiological metric for monitoring an individual's physiological and emotional responses, thereby offering an indirect assessment of their Situation Awareness (SA). SA refers to a person's awareness and comprehension of environmental events. Variations in heart rate, such as increases under stress or tension, can serve as indicators of an individual's reaction to specific situations. This paper explores the potential of heart rate monitoring technology to evaluate these responses, emphasizing the application of heart rate detection technology.

1) Heart Rate Variability (HRV): HRV measures fluctuations in heart rate within a normal range and is often used as an indicator of autonomic nervous system function. Research has employed HRV as a tool to assess stress levels and emotional states in individuals.

2) Non-contact heart rate detection: heart rate detection through video data captured by a camera can be used in the future in the medical industry and home monitoring, which has a large development prospect[10].

3) Millimeter wave radar-based heart rate detection: this technique allows senseless and contactless monitoring of heart rate by detecting the phase change of FMCW signal at a specific Range bin due to small vibrations of the target.

4) Non-contact heart rate detection system based on video analytics: this system can detect heart rate non-contact by analyzing facial videos, which can be used in some cases to monitor the physiological state of an individual.

5) Heart rate monitoring device industry: The development of the HRMS industry is closely linked to the global and Chinese macro-economic environment, which indicates that HRMS has a broad application in the field of health monitoring.

6) Optical heart rate monitoring (OHR): A technique that measures heart rate and tracks blood flow variations by emitting light that penetrates the skin. It then captures the light reflected back to a sensor, which is utilized to monitor cardiac activity.

In summary, while heart rate detection technology itself does not directly measure levels of situational awareness, it can be used as a physiological indicator for assessing how an individual is responding to a given situation. Monitoring heart rate fluctuations offers indirect insights into an individual's physiological condition, allowing us to infer their cognitive and emotional reactions to environmental stimuli. However, it should be noted that heart rate data is only part of the assessment of situational awareness, and needs to be combined with other methods and indicators for a comprehensive assessment.

5. Electroencephalography (EEG)

The level of Situation Awareness (SA) is assessed by electroencephalography (EEG) monitoring, mainly based on the ability of EEG to reflect the characteristics of brain activity. Situation Awareness involves an individual's ability to perceive and comprehend environmental occurrences, as well as to anticipate possible future events. EEG, as a non-invasive, high-resolution brain function monitoring tool,

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can capture the brain's response to stimuli in real time, thus directly assessing an individual's Situation Awareness.

1) Characteristic changes in EEG: Characteristic changes in EEG signals, for example, power, phase lock, and coherence, may reflect the neurophysiological responses of the brain to certain tasks. For instance, the rise in alpha-waves can be related to the relaxation of the environment, while the increase in beta-waves can be related to attention concentration [12].

2) Multimodal monitoring: A multi-modal monitoring approach that combines functional near infrared spectroscopy (fNIRS) with EEG is used to measure cerebral hemodynamics and lectroencephalographic activity at the same time, providing more comprehensive information about brain function [13]. This integrated approach is particularly suitable for complex tasks that require precise localization of brain activity and blood flow dynamics, such as flight simulation or situational awareness assessment in complex operational tasks[14].

3) Quantitative EEG metrics: During general anesthesia, various quantitative EEG metrics are employed to monitor anesthesia levels and can be linked to situational awareness. These include the Bispectral Index (BIS), Entropy Model, and Narcotrend Index.

EEG monitoring holds significant promise as a tool for assessing and monitoring situational awareness. By analyzing the characteristic changes of EEG signals, combining multimodal monitoring techniques, and quantifying EEG metrics, researchers can gain a deeper understanding of the brain's activity patterns under different tasks, and thus assess an individual's situational awareness ability. It should be noted, however, that the interpretation of EEG signals requires specialized knowledge, and the accuracy of the monitoring results may be influenced by many factors, such as signal quality, analytical method selection, and individual differences.

6. Eye tracking

The monitoring of situational awareness levels through eye-tracking technology is mainly based on the characteristics of an individual's eye movements when processing information. Eye tracking techniques can record eye gaze points, gaze duration, saccades, and smooth pursuit movements, all of which reflect an individual's perception of the environment and cognitive processing.

1) Eye Movements and Attention: Eye tracking techniques are often used to assess an individual's visual attention allocation. In complex tasks or situations that require high situational awareness, such as flight simulation and medical diagnosis, there are significant differences in eye movement patterns between experts and novices, which may serve as a measure of situational awareness [15].

2) Gaze point analysis: In tasks with high situational awareness requirements, professionals tend to focus their eyes on critical information. By analyzing an individual's gaze point distribution and gaze duration, one can infer his or her situational understanding and situational awareness level.

3) Changes in pupil diameter: Variations in pupil size, through dilation and constriction, provide insights into how individuals allocate attention and react emotionally to different stimuli. For example, fluctuations in the size of the pupil can serve as indicators of cognitive load during complex scenarios [16].

In summary, eye-tracking technology can be used as an effective means to monitor the level of situational awareness by analyzing the eye movement patterns of individuals under specific tasks. By applying eye-tracking technology in a variety of tasks and scenarios, previous researchers have demonstrated the potential and application value of the technology in assessing situational awareness. Future studies should aim to enhance the precision and dependability of eye-tracking technology for its application in real-world scenarios.

7. Conclusion

This article thoroughly examines the concept of situational awareness (SA), highlighting its significance and various evaluation approaches. It outlines the three tiers of SA and underscores the necessity of achieving superior situational awareness in dynamic settings. Furthermore, it explores diverse research domains within SA, such as states, systems, and processes, and introduces methods for both direct and indirect measurement of SA. The discussion on monitoring techniques focuses on the utility of physiological indicators to gauge SA. Methods like heart rate monitoring, EEG, and eye tracking

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are presented as objective means to measure an individual's situational awareness by capturing physiological reactions to particular scenarios. These methods are especially effective in demanding situations that require swift and precise decision-making, including flight control, medical diagnostics, and emergency response. The article concludes with the assertion that although physiological monitoring offers a significant method for evaluating SA, these techniques must be refined for enhanced accuracy and reliability in real-world applications. Additionally, the integration of these tools with other assessment strategies and metrics is recommended for a more holistic analysis of situational awareness.

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