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Advanced situation awareness, Human Vigilance, and Sensitivity in complex and dynamic Industrial systems: Perspectives towards enhancing Systems resilience under digitalization contexts

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Emerging industrial systems and solutions are such that the inherent complexity of the system, coupled with highly dynamic conditions, demand operators to perceive and judge abnormal situations, predict multiple scenarios based on unwanted deviations, and take proactive measures much ahead of time. The issue of how to enhance human situation awareness (SA) in such modern highly complex, interconnected, and dynamic systems is raising concerns of systems developers, asset operators, and authorities, especially when automation and digitalization show tendencies to keep the human "out of the loop" fully or partially. Based on recent industrial incidents and observations, we argue that the contemporary understanding of SA should be developed to an advanced SA level, the so-called Advanced Situation Awareness (Ad-SA), to ensure systems resilience early by mitigating potentials for unwanted events and losses. With respect to advancing digital solutions and applications, this paper is scrutinizing human vigilance and human sensitivity as critical integral issues towards such Ad-SA. Some selected industrial cases are reviewed to support arguments and to shed light on the pragmatism towards such new thinking.

Keywords: Situation Awareness, Abnormalities and Deviations, Vigilance, Sensitivity, Resilience, Digitalization, Advanced Situation Awareness, Complex industrial systems, Industrial assets.

1. Introduction

Human situation awareness (SA) is a critical factor in every high-risk industrial system (Pew, 2017; Sarter and Woods, 1991). Such industrial systems are exposed to various internal and external forces, that can affect how diverse elements of the system interact with each other at different times and in different operational phases. All such effects and interactions between systems elements and their response patterns possess inherent uncertainties. Small changes in one component or sub-system, or indeed in the environment (local or global) can cause unstable or vulnerable conditions leading to loss of integrity, or core purpose (Almedom, 2013).

Under modern advanced and digital conditions, industrial systems need a technological, human, and organizational edge over abnormalities, deviations, and unexpected events to avoid major losses. Enhancing and maintaining a human edge is a critical necessity to ensure resilience of modern and emerging industrial systems that are complex and highly dynamic. From a more advanced perspective, it is argued here that SA needs to be developed to a higher level in such modern industrial systems that enable humans to deal with systems abnormalities ahead of time as a pre-condition to enhance resilience under dynamic and chaotic conditions.

As Proctor (2018), Illankoon (2020), etc. elaborate, under normal circumstances operations can be performed in known patterns and predictable ways based on a level of familiarity with situations. Operators follow routine operations, form their judgment with less effort, and take actions according to well-practiced responses to system behaviour to operate the systems within a pre-defined safe envelope. On the contrary, operators can encounter serious challenges when the system deviates from a normal state of operations. When industrial systems get more and more complex and get exposed to numerous abnormalities, subsequent changes within the system can result in raising immediate demands on operators (Vinnem and Liyanage 2008). Ideally, operators should be able to understand abnormalities ahead of time in those situations and make early decisions according to their reasoning about the systems' deviations and state (Proctor, 2018).

Even though automated and semi-automated systems in the new industrial era have opened a window of opportunities for operators to monitor, maintain, diagnose, inspect, and recover operations in dynamic environments, the cognitive role of humans to monitor real-time data and control system information cannot be eliminated or neglected. Humans should be able to perceive and interpret information among numerous real-time data in such dynamic environments, and hence evaluation of human cognitive abilities in the digital work environment is critical from both safety and operational perspectives (Lin et. al., 2013).

Subsequently, it is hereby argued that the conventional perspective of SA cannot address all concerns and gaps in the era of intelligent systems, and some new knowledge is required to fill these widening gaps between the human cognitive ability and the pace of change.

2. Human Factors in Complex Systems

As intelligent solutions increasingly become popular, industrial systems also change dramatically making new demands on operators (Skilton and Hovsepian, 2018). The real challenge in modern and emerging industrial systems is such that the inherent complexity of the system, coupled with highly inter-connected, and dynamic conditions, demands more capabilities of humans, inclusive of continuous attention, better insight, logical reasoning, deeper knowledge, etc. under changing conditions. Some industrial contexts can be even more demanding when automation and digitalization take the human fully or partly "out of the loop", affecting human performance, particularly under abnormal conditions (Kaber and Endsley, 2004). Longer system recovery times and inefficacious response to systems abnormalities imply a much higher potential for further escalations of early deviations to more demanding or uncontrollable conditions further leading to unwanted events and incidents.

In modern industrial contexts, automated decision aids and expert systems can be seen implemented to help assist or speed up decision-making processes (Proctor, 2018). It is often assumed that utilizing intelligent systems reduces the need for human intervention and hence human attentional efforts. However, as Illankoon (2020) and Proctor (2018) argue, industrial contexts that limit humans from acquiring information from the environment and cause humans to invest less effort and attention can adversely affect human situation awareness when abnormal situations occur. Such industrial conditions that hinder humans to make early decisions naturally can jeopardize the reliability, safety, and security of industrial systems.

According to (Endsley and Garland, 2000), in order to enhance human SA in dynamic and complex systems operators must pay attention to a range of influence factors and leverage various capabilities, knowledge, and skills within pre-defined rules to work among many uncertainties and challenges. It is argued here that in the light of advancing industrial digitalization, a new focus is needed on the so-called *Advanced SA* (Ad-SA) as a critical pre-condition to enhance and strengthen the resilience of highly complex and dynamic industrial systems.

The following sections further elaborate on the Ad-SA, where human vigilance and human sensitivity play integral roles as a key to dealing with abnormalities and deviations under complex systems demands.

3. Situation Awareness (SA) as a Continuous Process

In general, SA concerns the ability of individuals to perceive, understand and judge a condition. Many definitions of SA can be found in literature, especially from cognitive and psychological perspectives. For instance, Endsley and Garland (2000, p.5) has defined SA as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*". Endsley's SA model elaborates on how humans employ information processing to acquire SA. Accordingly, it is possible to identify three specific levels of situation awareness as elaborated in Table 1 (also see Pritchett et. al., 2000).

Table 1 Description of three levels of SA

SA Level	Attributes
Level-1	Data is received and information is perceived by humans. It is significant that the operators are sensitive to the right data sets at this level for proper judgment.
Level-2	Judge the meanings of information received and comprehend the situation. This can be affected by the level of prior experience and knowledge.
Level-3	Make judgments about implications and predict the future state. Subsequently, lead to a relevant response within the dynamic environment.

As Pew (2017) pointed out, it is crucial to know that situation awareness is context-dependent. If the condition is stable, then the level of SA that operators need to assess the condition can be constant. However, contexts and conditions are changing continuously in a dynamic environment with time. A situation is defined by a set of conditions in such an environment where humans need to have ample attention to evaluate the situation, design a plan and take proper action to interact with conditions. This implies that the level of knowledge and information required to accomplish a certain state of awareness to perform a particular task for system recovery should be identified properly. Moreover, under both normal as well as abnormal situations, relevant boundaries should be understood as practically clear as possible to say when, where, and how the situation has and can be changed. There have been some different perspectives about the current models of SA that point out they should be enriched to address growing concerns as systems are becoming more complex, interconnected, and technology-driven (see, for instance, Chiappe et. al., 2012; Salmon et. al., 2012).

Industrial systems developers and operators need to recognize how humans select, combine and integrate information to judge the situation on a continuous basis, and to make demanding decisions within a given time and space in a given changing context. Thus, it is debatable if SA can be considered as a specific state or as a product within a context without fully realizing its inherent dynamics.

It is becoming increasingly difficult for users and operators to comprehend multiple changing conditions and to make sense of them in many high-tech contexts to mitigate the potentials for unexpected events. It is also difficult to develop and maintain thorough situational awareness especially from remote locations during continuous operations. This has called into question if the current state of knowledge on SA is adequate to deal with real challenges in modern and future highly demanding industrial contexts. Thus, rather than resorting to the conventional approach as Stanton et. al. (2001) underlines, where SA is seen as a specific cognitive state dependent on information and knowledge available at a specific point in time, it is argued here that SA should be advanced as a continuous process which needs continuously engaging cognitive processes and supportive measures to help realize underlying dynamics under change-sensitive industrial contexts (see Figure 1).

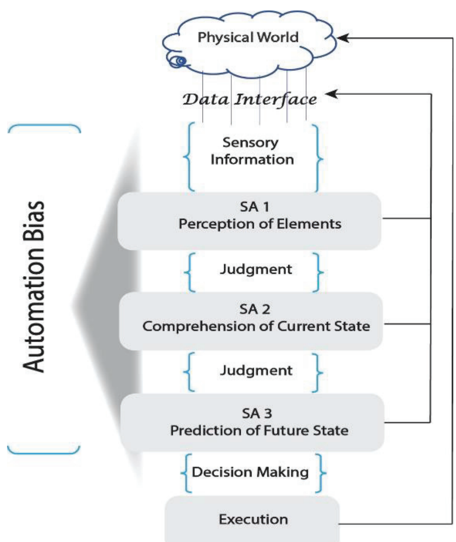

Fig. 1. SA as a Continues Process in highly dynamic environments

The SA levels 1-3 discussed in Table 1 provide the basis towards defining SA as a continuous process, as illustrated in Figure 1. It emphasises the continuous need to acquire, maintain, and refine the required knowledge about a situation. In order to ascertain and enhance a pre-judged situation of current and future state, more data needs to be captured and incorporated into highly-dynamic contexts. This is particularly so in circumstances where a system undergoes unknown or abnormal conditions. However, in many modern industrial contexts automation bias has begun to act as a competing factor towards a given level of SA.

As high technology systems are increasing the control on cognitive tasks, the concept of automation bias is gaining more attention as an influencing factor when people are inclined to rely more on automated aids (Parasuraman and Manzey, 2010), and when they use specific solutions generated by the system itself without looking for additional or contradictory information under abnormal or unfamiliar conditions (Cummings, 2017). Such automation bias, according to Dzindolet et. al. (2001), can be caused by; cognitive miser due to the use of simpler heuristics, trust in automation aids, trust that automated systems are tremendously versatile, and diffusion of responsibility, that can consequently reduce the human effort to think, evaluate, and analyse.

Moreover, although simple heuristics enable human judgment when quick action is needed, according to Mosier and Skitla (2018), poor judgments leading to human errors can be rooted in using such simple heuristics to make decisions in an abnormal condition. Similarly, over-reliance on an automated system can also adversely affect users' attention to aberrant events. In the event of an abnormality, the most salient cues can bias human responses more than other stimuli. On the other hand, people are unlikely to notice implicit abnormalities with no or even less salient cues which cannot draw their attention (Wickens 1991).

4. Introducing Advanced Situation Awareness (Ad-SA)

As Harrald (2006) emphasizes, abnormalities that are encountered during a rare event can be unique and unanticipated, and thus an appropriate response is often improvised. Therefore, to have a high system resilience, new technological systems must enhance SA by providing humans with sensemaking capabilities and not to impede it by emphasizing only on importance of data transformation processes (Harrald and Jefferson, 2007). In general, the contemporary perspectives of SA that are mostly rooted in the second world war, need to be re-developed to an advanced level, which in this paper is discussed as *Advanced Situation Awareness (Ad-SA)*.

When modern industrial systems are subjected to complex operating conditions, they generate higher potentials for a wide range of abnormalities, deviations, rare events, and incessant changes. Ad-SA is a necessary contributing factor to enhancing the resilience of such systems. With the growing concerns that highly complex and dynamic systems can and do fail in complex patterns (Wilson 2003), Ad-SA also aims at providing new measures and opportunities for operators to detect abnormalities and deviations in an early stage and redirect their pathway to ensure high system resilience. Indeed, as the success to achieve such high system resilience depends on various factors, the concept of Ad-SA calls for a more holistic as well as an in-depth approach w.r.t. specific conditions in specific contexts.

In Ad-SA, the relevant information among huge data should be picked up and perceived at the most advantageous time and pace. Judgment and discernment ability is central to the enhancement of operator sensitivity to engage, think critically and creatively, share ideas, and use unbiased judgment for enhanced decision-making. For instance, USA Army (2021), has identified such attributes as the core of an ideal operator in demanding contexts. In order to realize such abilities, operators should be vigilant to scan their environment precisely and be quite sensitive to implicit and explicit cues and signals. This implies that in Ad-SA, humans need to be able to capitalize on the two specific properties namely, *vigilance* and *sensitivity* to changing dynamics where numerous components or agents are interrelating in diverse ways and states are changing over time.

4.1. Human vigilance

Researchers such as, Warm et. al. (2008), and Proctor (2018), describe vigilance as the state of being alert. Human vigilance helps operators to maintain their minds focused on a particular task for a relatively long period by controlling their attention selectively or dividing attention between several sources (Langner and Eickhoff, 2013). Vigilance as a human ability has become an increasingly interesting field lately since it has begun to play a vital role in dynamic environments where real-time data is of paramount importance (Proctor, 2018; Warm et. al., 2008), for instance, to detect any rare event and abnormal signals in an operating industrial system.

According to Parasuraman and Mouloua (2018), execution of vigilance in a dynamic environment is a high cognitive activity. An experiment conducted by Mackworth (1950), has even shown that in such conditions, reaction times can become slower over time (Proctor, 2018). Some studies have also shown that sustaining attention to simple and monotonous tasks can be very difficult and frustrating over time due to low arousal levels in comparison to highly cognitively engaging and interesting ones (Langner and Eickhoff, 2013). However recent studies have also argued that lack of information-processing resources and their weak operational interfaces can cause vigilance decrement rather than the effects of other parameters (Grier et. al., 2003).

4.2. Human sensitivity

Human sensitivity to industrial stimuli is a significant ability in the retrieval and understanding of environmental information and therefore perceptual judgment. People differ in their sensitivity level to various stimuli existing in a dynamic environment. Human sensitivity to stimuli can be considered at an acceptable level if they can detect right signals in the presence of irrelevant ones such as false alarms. However, when there is no way to discriminate irrelevant signals from relevant ones, human sensitivity towards environmental stimuli can result in biased judgment. Moreover, when the complexity increases, human sensitivity can decrease, affecting the response time (Proctor, 2018). At the same time, human perception can also be influenced by the multisensory integration process in the brain (Moorhead et. al., 2004).

5. Enhancing Resilience of Modern Complex System Through Ad-SA

As Parasuraman and Mouloua (2018) underline, although one goal of automation is changing human roles from active to supervisory control, it is also needed to provide a middle ground. A better resolution to enhance both human vigilance and sensitivity requires a better understanding of cognitive functions around dynamic contexts and new hybrid measures to support human abilities, to enhance human performance under demanding operating contexts.

Hoffman and Hancock (2017) have defined resilience as the ability of a system to achieve either a new state of stability or tolerate perturbations as a new normal state. As Fairbanks et. al. (2014) point out, the success of achieving high system resilience depends on various factors such as technology, workspace configuration, communications level of knowledge, cognitive ability, capability, etc. to recognize deviations in early stages. However, there is always a lack of knowledge to cope with abnormalities in complex systems due to inherent uncertainties. As a result of abnormalities, a system can be pushed beyond defined limitations and exhausts its capacity. Elaborating on abnormalities, Harrald (2006), emphasizes that when they are encountered, responses can often be improvised. Therefore, underlines Harrald and Jefferson (2007) that technological systems must enhance SA to ensure a high system resilience by enabling humans with better sensemaking processes. The scope of Ad-SA in essence is to provide such opportunities for humans to have increased vigilance towards what is going on in addition to specific capabilities to be sensitive to critical signals and to detect deviations in early stages. In general, Ad-SA-enabling solutions should be able to inform operators that there is something they should focus on, prioritize their attention, and ignore irrelevance while searching for possible scenarios and effective counteraction pathways. As De Carvalho et. al. (2011) argue, when operators can predict consequences and upcoming scenarios, they have more time to prepare and execute counteraction plans under critical conditions. Though all factors in a complex system cannot be controlled but being sensitive to the right cues and being vigilant to monitor complex processes continuously can lead to a higher level of situation awareness which can assist humans to detect potential deviations in the early stages.

From an SA perspective, Figure 2 illustrates three scenarios in terms of resilience capacity in a dynamic industrial context. In the first scenario, the poor system resilience is correlated to the lack of SA. A low level of SA can increase susceptibility to abnormalities in a complex system. The second scenario shows that general situation awareness can assist operators to cope with rare events and to return the system to normal conditions. However, the success here is not guaranteed in highly-dynamic contexts because implicit abnormalities can cause various types of pattern evolution due to interconnected components and variables. The third scenario occurs with specifically enabled abilities to early identify deviations where operators can have the advantage of time and capacity to deal with such early-sensed deviations.

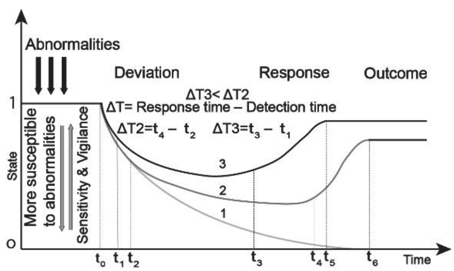

Fig. 2. Ad-SA as a necessary condition for enhancing Resilience of Modern Complex and highly dynamic Systems

Preliminary reviews of some recent accidents clearly indicate how Ad-SA would have helped to gain better resilience while mitigating risks early under demanding contexts. Two such cases are briefly discussed below.

5.1. Ad-SA in offshore drilling rigs

According to Andersen and Albrechtsen (2011), drilling for oil and gas and well operations are continuous problem-solving processes. The drilling crew should be prepared for any changes in drilling plans due to a great deal of uncertainty, for instance in weather conditions, logistics, technical variables, and importantly downhole conditions that are not predictable. Although integrating and automating drilling services, real-time wellbore monitoring, and technical support from remote operation centers can provide a clear view of operations to deal with challenges in this uncertain environment (Liyanage and Bjerkebaek 2006), maintaining and enhancing SA to detect deviations in early stages in order to take a quick counteraction are still critical factors to prevent accidents.

The details uncovered by the case investigation of the Deepwater Horizon disaster, where 11 workers lost their lives (Sneddon et. al., 2013), provide ample evidence as to how Ad-SA would have played a critical role in mitigating the risk of a gas leak and an explosion, thereby preventing one of the most catastrophic offshore disasters in history.

The investigation (Bly, 2011) has uncovered that casing strings were run into the hole and the cement operation was done afterward. An integrity test had been performed, the mud was circulated out and displaced with seawater for temporary well abandonment. However, well integrity was not established, hydrocarbons came into the well and remained undetected. Hydrostatic pressure dropped gradually and well control was lost. Hydrocarbon ignited while the blowout preventer failed to seal the well. The review of the accident shows a series of abnormalities and deviations that has not received serious attention in a demanding and complex environment. Many latent issues and unsafe conditions consisting of technical, mechanical, organizational, and human issues came together to initiate and escalate the accident.

Deviation analysis indicates that although some signals were showing poor cement quality, people were not that sensitive to them, and cement evaluation logging was cancelled. The crews conducted a negative pressure test for good integrity, but the results were poorly interpreted, and no critical questions were raised to assess possible consequences. Drill pipe pressure showed a higher value rather than expected. The crew did not look for more information to explain the causes, they interpreted the deviation as a U-tube effect instead. They had not anticipated the consequence of negative pressure test failure in their actions (Bly, 2011; Roberts et. al., 2015).

According to available case data (Bly, 2011; Roberts et. al., 2015), it appears that some pits were bypassed for cleaning and other activity, which indicated some challenges in monitoring the volumes that came from the well. Even though the investigation proved that the information was perceived in many stages, the crew could not integrate and interpret information appropriately to judge the situation and could not identify potential risk scenarios towards unwanted situations. For instance, after several attempts to bleed off the pressure in the drill pipe, the higher pressure was interpreted as a normal issue (bladder effect) which had happened several times retrospectively. The crew relied on this wrong interpretation that potentially came from faulty priory knowledge or lack of cognitive involvement, instead of exploring and gathering more information to judge the real situation under specific uncertain conditions.

According to Endsley and Garland (2000), human attention decreases in a dynamic environment with multiple competing cues. When cues and signals are perceived in this environment, they should be integrated and compared with the historical data to judge the current situation and predict future states. Some factors drew the drilling crew's attention which prevented them to monitor continuously what was happening in the well. For instance, the mud leakage problem in the riser and the presence of visitors may have drawn the crew's attention from the last negative pressure test (Roberts et. al., 2015). Pit cleaning and transferring mud between pits as preparation for the next operation confused the crew that the well was static. They did not try to calculate the volumes for any possible gain in pits as they expected the logs to show any changes in the pits whilst some pits had been bypassed (Bly, 2011).

In a more thorough analysis, many more interesting details can be uncovered from this accident that underlines the critical role of Ad-SA that counts on enhanced human vigilance and sensitivity towards the assurance of resilience in demanding industrial contexts.

5.2. *Ad-SA in aviation sector*

Although resilience is an operational concept, Burton et. al. (2021) emphasize that it should be considered from design to operations to enhance the resilience of complex systems. Recent Boeing 737 MAX-8 accidents point out the fact that abnormalities and deviations that systems go through at various stages of systems development and operations had pre-defined the conditions for the accident.

According to Johnston and Harris (2019), Boeing decided to change the engine size to achieve better fuel efficiency. The new engine position and its size could impose an increasing stall risk on the new aircraft. To address this issue, the manoeuvring characteristics augmentation system (MCAS) was further developed.

Details of the case reveal that issues that truly challenge human cognitive engagement patterns had not been taken into consideration from very early stages. Boeing seemingly had tried to do technical improvements without being able to fully analyse or predict all consequences. Hardware design flaws, as well as pilot reaction patterns, indicate the presence of an incorrect mental model to process information (Johnston and Harris, 2019). In both deadly accidents involving 737 MAX-8, pilots had fought against the automated system. Despite all efforts, they had failed to control the aircraft, even though in the Ethiopian Airlines case the pilots had heard about the new software. The pilots appeared to have acquired some SA to detect the problems at least in the second accident, but there had been little time to react. Apart from the two fatal accidents, there had been few cases where Pilots' higher level of SA had enabled them to deal with unexpected conditions based on due early attention to design and operational deviations. Johnston and Harris (2019) have underlined in their studies that there were economic, technical, and organizational demands that led to the disaster. The case investigation has also uncovered many contributing factors, including poor documentation, rushed release, delayed software update, humans out of the loop, etc.

Detail review of the Boing 737 Max-8 accidents clearly shows that if Ad-SA had been enabled throughout from new concept development to commissioning and operational processes, with an enhanced vigilance and sensitivity under the change-engineering and demanding operational contexts, then those major accidents would have been prevented.

6. Conclusion

As stated by Almedom (2013), in a complex system it is hard to determine all boundaries precisely and judge where the system starts and ends because of many interconnected agents and extended interactions. Any component can control a few more components while they can affect the whole system. Hence, abnormalities can emerge due to various interactions and relationships that exist within a system and they cannot be fully eliminated. An abnormality is an inherent characteristic of any system. Ensuring a high-resilient system in such environment requires more focus on human cognition capability as an important proactive means to activate diverse responses to deal with unexpected events. Implementation of an automated system without considering human cognition is completely pointless. Rather, the assurance of human ability (and capability) to work reliably, safely, and securely in a complex and dynamic environment where abnormalities are more frequent is a key to coping with unwanted events. Therefore, as many industrial incidents and accidents have recently proved, achieving Ad-SA based on enhanced human vigilance and sensitivity is gradually becoming a critical need to ensure high-resilience of such systems and contexts.

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