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OPERATOR SITUATIONAL AWARENESS AND SYSTEM SAFETY

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INTRODUCTION

Studies of the dependency between complex, dynamic systems and their human operators often focus on human-computer interactions without considering the emergent properties of human-machine systems in use. As systems become more complex, and typical operating environments more dynamic, the role of the operator has typically changed from providing manual to cognitive control. The nature of the interaction in these modern systems has changed from physical work with the body to cognitive work with the mind. This view is characterised by the 'glass cockpit' design of many modern aircraft where the pilot is often removed from direct manual interaction to assume a system management role.

An understanding of human cognition in context is thus central to the design of human-machine systems and this is particularly pertinent in safety-related systems when the elimination of hazards is a principal concern. This paper will begin with a brief discussion on the nature of the hazards peculiar to the safety of human-machine systems in the context of their use.

For complex systems in dynamic environments, an operator must to pay attention to a large volume of information from a variety of sources including sensors and other operators in order to acquire an awareness of the situation in question. In many cases humans are no longer able to appreciate the true situation without the aid of machines. Machines must therefore tell us more of what we need to know and they must do it more effectively and less ambiguously than before.

The design of human-machine systems can have a profound effect on operator awareness of the system environment and ultimately upon system safety. This paper will argue that operator situational awareness is an important phenomenon that can be used to examine human cognition in context. The paper will briefly introduce the dominant theoretical perspectives on situational awareness. Based on this discussion, a Situated Cognition perspective of situational awareness is examined and an Interactive System Safety Analysis Method is introduced.

The paper will outline how the Interactive System Safety Analysis Method was used as a framework for the analysis and identification of hazards relating to operator awareness in the context of system use. Specifically, the paper will suggest how the method can be used for the identification of interaction hazards affecting operator situational awareness that can lead to system hazards in safety-related applications.

HUMAN FACTORS AND SYSTEM SAFETY

Safety-related systems generally contain hazards that originate from both technical and human sources. Modern technology, particularly Information Technology, is often extremely reliable and hardware reliability engineering is a relatively mature discipline. Consequently, technical hazards are often relatively easy to identify and their associated risks can be quantified with the many different engineering techniques available.

In contrast, human-related hazards are relatively very difficult to quantify and these are often neglected by systems designers as a result (1). Human factors are repeatedly mentioned as a major contributing factor or even the direct cause of accidents or incidents. For example, an analysis of causal factors contributing to a situation in which the safety of aircraft was compromised show that nearly 98% of all incidents that occurred in UK airspace during 1997 were caused by human error (calculated from 2 and 3).

This may be due to the increased complexity introduced when dealing with the human factors of a system. While hardware reliability techniques are relatively mature and well understood, this is not the case when dealing with human reliability. It is generally very difficult to predict all the possible mental states of an operator in a complex system. Even if it were possible to identify all the possible mental states, and their effects on human behaviour, the difficulty of estimating the probability of occurrence of each state remains.

Human Reliability Analysis techniques have attempted to address this issue, however, much of this research has been dominated by assumptions that apply to technical systems and often these do not translate to human systems (4). It may be argued that human error is best examined from a cognitive perspective, as traditional reliability engineering techniques do not appear to fit well with human factors concerns.

Human-machine systems present unique hazards and problems when developing safety-related systems. Human error is repeatedly mentioned as a major contributing factor or even the direct cause of accidents or incidents. The design of the human-computer interactions can have a profound effect on safety assurance, particularly during emergency situations. When emergencies arise, and system operators must react quickly and accurately, the situational awareness of the operator is critical to their ability to make decisions, revise plans and to act purposefully to correct the abnormal situation. This sentiment emphasises the importance of designing system interactions and interfaces to explicitly support situational awareness in safety-related systems.

OPERATOR SITUATIONAL AWARENESS

Situational awareness (SA) has become a common phrase for both system designers and operators who often base its use on an intuitive understanding of its definition. Sarter and Woods (5) have identified SA as a critical, but ill defined, phenomenon and others have also noted that it is difficult to find an accepted definition of the term (6). Nonetheless, SA has been the subject of much research in recent years, particularly within the field of aviation and other similarly complex domains (7, 8).

In the context of human-machine interaction, current definitions are generally based on opposing views of SA as either a cognitive construct or as an observed phenomenon. The cognitive perspective is the prevalent view (characterised by Endsley's (9) well cited theory) which sees SA as a cognitive phenomenon that occurs 'in the head' of the user – though even within this broad perspective there are differing interpretations and emphases. In contrast, if seen as a behaviourist construct, SA becomes an observable abstract concept located 'in the interaction' between user and environment. Despite the theoretical differences that exist, a combination of ideas from both perspectives can be used to help to understand cognition *in situ* leading to a Situated Cognition perspective of SA.

As the preceding discussion has highlighted, there are competing and sometimes confusing views on SA and its relation to people and the situations in which they are operating. There is currently significant on-going research to further these debates and refine these perspectives. Whilst such research is of long-term value in contributing to the maturity of the field and refining explanations of SA, this paper takes a more pragmatic approach, arguing that a view of SA which incorporates features of both the cognitive and behaviourist perspectives may be more immediately useful to practitioners.

A synthetic and pragmatic perspective sees SA as a measure of the degree of dynamic coupling between a user and a particular situation (10). This view attaches importance both to the user's cognitive state and to the context or situation in which they are acting, reflecting a move away from traditional information processing models of cognition towards the situated cognition (and situated action) perspective.

A tangible benefit of this perspective of SA is the focus on the inseparability of situations and awareness (10). Discussions of SA focus attention on both what is inside the head (awareness from a cognitive perspective) and also what the head is inside (the situation which provides observable data) (11). Generally, this stance suggests that the user's current awareness of a situation affects the process of acquiring and interpreting new awareness from the environment in an ongoing cycle.

SA is a term often used intuitively to describe the experience of comprehending what is happening in a complex, dynamic environment in relation to an overall objective or goal. Regardless of theoretical perspective, it is generally accepted that this experience involves both acquiring and maintaining a state of awareness (9, 12) in a continuous cycle. The dynamic nature of this continuous process implies that SA requires the diagnosis of past problems and the prognosis and prevention of future problems based on an understanding of current information. Consequently, it is suggested here that a pragmatic SA framework must be inherently dynamic and responsive to environmental changes.

This pragmatic perspective acknowledges the equal importance of both the *product* of SA and the dynamic *process* of directed consciousness required to acquire and maintain SA. Within this perspective, SA can broadly be viewed as the fit between a subjective interpretation (awareness) of a situation, built through the individual's interaction with their environment, and an objective measure of the situation (13).

The implications of this Situated Cognition perspective of SA are important. This view of SA acknowledges the equal importance of both the interactive *process* of acquiring and maintaining SA and the user's awareness, or *product* of SA, built through a continuous interactive process. From this discussion, it can be argued that it is necessary to develop methods that help system developers to analyse and assess both the product and process of SA.

AN INTERACTIVE SYSTEM SAFETY ANALYSIS METHOD

From this Situated Cognition perspective of SA, equal emphasis is placed upon the evaluation of both the product and the process of SA. Practical methods are therefore required to help developers to evaluate the design of human-machine systems and specifically to measure their contribution to SA. An Interactive System Safety Analysis Method (ISSAM) has been developed which is based upon the Situated Cognition perspective of SA (14). ISSAM proscribes the concurrent application of two different techniques namely, the Situational Awareness Process Analysis Technique (SAPAT) and the Situational Awareness Global Assessment Technique (SAGAT) to evaluate the process and the product of SA respectively. These techniques will be briefly introduced before a description of the application of ISSAM is presented.

SAPAT - Evaluating the Process of SA

SAPAT is based upon Sandom and Macredie's (15) SA Process Model and this technique is used as a framework for identifying problems associated with the *process* of acquiring and maintaining SA in safety-related environments. The SA Process Model is specifically used to identify potential or actual SA interaction problems relating to safety.

The SA Process Model (shown in Figure 1) is adapted from Neisser's Perception-Action Cycle (16) which focuses on the adaptive, interactive relationship between an operator and his or her environment. As an operator begins to interact in the system environment, they can be considered as moving along the spiral in the model from the central point.

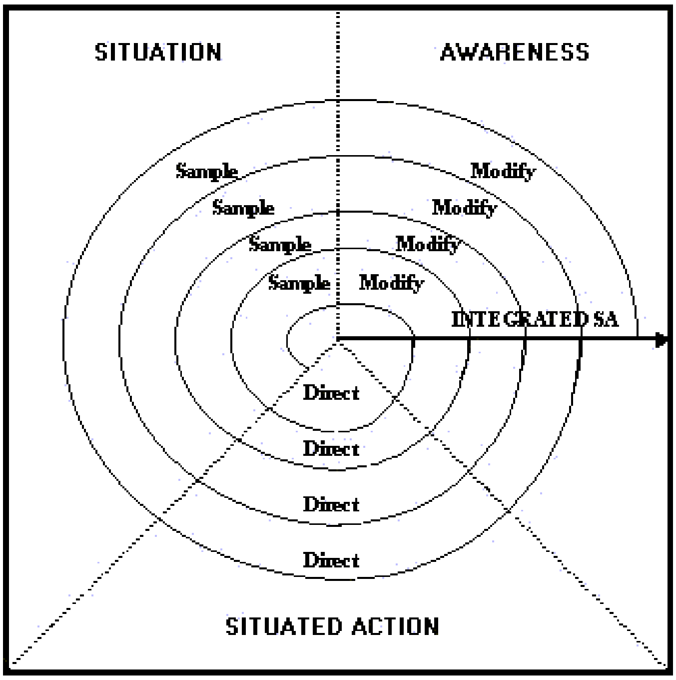

Figure 1 - An SA Process Model (adapted from Neisser (16))

An operator may start anywhere in the cycle as, for example, a routine may take over to provoke initial action. Starting arbitrarily, the individual will *sample* the situation, building a perception of it by extracting and interpreting information content. This may lead the individual to *modify* their awareness, developing their mental representation of the situation in which they are interacting. Changes in the individual's interpretation of the situation cause them to consciously *direct* their action (including what/where to sample next), anticipating future states in which they might find themselves and acting accordingly. The 'sample–modify–direct' cycle which the individual can be thought of as having passed through will have developed their awareness in a particular way. As time progresses the individual will cycle through these phases building an integrated awareness that grows with each iteration.

SAPAT and the SA Process Model can be used as a framework for the identification and analysis of situated hazards relating to operator awareness in the context of system use. There are two specific ways in which the SAPAT technique can contribute to the design of safer systems: identifying interaction breakdowns and identifying automatic interactions, both of which are key to SA. Differentiating between these two modes of cognition using SAPAT enables us to highlight and compare different aspects of human action which will be of use to the improved design of human-machine systems.

It is possible to use SAPAT to identify hazardous interactions which are carried out automatically without the operator modifying their awareness. The SA Process Model used within SAPAT can also provide design guidelines relating to analysing difficulties that affect the user-system coupling, such as interaction breakdowns. The division of the model into areas of activity on the individual's part (sample–modify–direct) provides a structure for practitioners and researchers to analyse and categorise SA-related problems. For example, the SA Process Model was used to question where the problems in particular situations might have arisen: what information did the WCs sample from their environment?; how did this lead them to modify their awareness (what information was available through the interface)?; and how, subsequently, did this direct the WC's situated actions?

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SAGAT - Evaluating the Product of SA

Endsley's (17) Situation Awareness Global Assessment Technique (SAGAT) is used in ISSAM to evaluate the level of the operator's subjective awareness during the field-study. Briefly, the SAGAT technique requires the production of high-fidelity simulations, simulation scripts, probe questions and the careful choice of a representative sample population. The SAGAT simulations are then run and frozen at different points and the operator answers domain-specific probe questions.

This application of SAGAT enables the system developer to quantify the product of operator SA through repeatable simulations. The quantitative results from each simulation is taken as the safety benchmark for the interactive system in terms of its SA support to provide a comparative safety analysis method. A similar safety analysis can then be undertaken for the evaluation of the system following significant system redesigns or even system replacement.

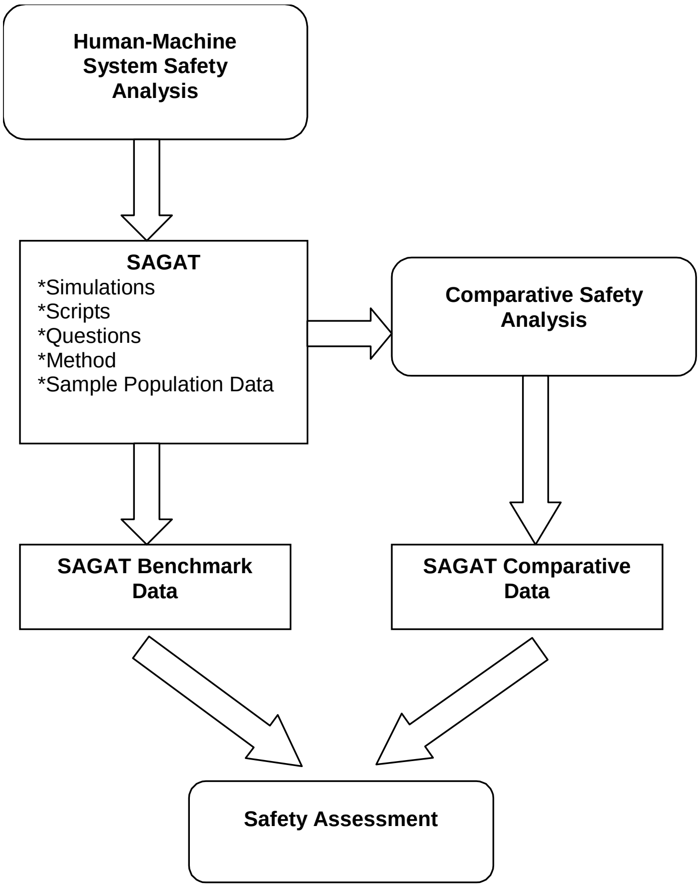

Figure 2 - Comparative Safety Assessment

This SAGAT-based comparative safety assessment technique is summarised in Figure 2. A system developer can assess the safety of a replacement human-machine system using the ISSAM SAGAT method. This will require the system developer to carry out an assessment of a replacement interface using exactly the same Simulation Development outputs (simulations, scripts, SAGAT questions) and Simulation Exercise conditions. Also, to use the SAGAT data for a comparison of system safety, it would be essential to ensure that a similar sample user population is used to remove any bias introduced through individual characteristics. The application of ISSAM provides quantitative benchmark safety data which can be used for comparison with other system interaction design solutions. This will provide a system developer with a method of assessing the safety of any interactive human-machine system relative to another.

A SYSTEM SAFETY STUDY

The United Kingdom Air Defence Ground Environment (UKADGE) system provides ground-based command and control services to military aircraft within the UK. The core capability of the UKADGE system is provided by the Air Traffic Control activity of Air Defence Fighter Controllers and also by the hardware and software of a system known as the Integrated Command and Control System (ICCS) which, together with data from other sources can compile an air picture of the UK.

The existing ICCS hardware is becoming obsolete and expensive to maintain and a project is being undertaken to replace the system with more modern, commercial off-the-shelf components. Many of the system changes will be transparent to the Fighter Controllers; however, a major tangible change will occur with the replacement of the existing ICCS interface components which will impact significantly on system interactions and activities.

From an operational safety perspective, the proposed changes to the system interface has been recognised as a major area of risk and a pragmatic method of assessing the relative functional safety of the replacement system was required. An empirical study of the UKADGE system was therefore undertaken to provide a method of assessing the relative safety of the existing system and to collect benchmark data against which a replacement system could be evaluated.

A Safety Study of the UKADGE system was therefore undertaken based on the Situated Cognition perspective of SA outlined previously. The UKADGE System Safety Study was conducted in two distinct phases which are briefly described here:

Simulation Development Phase

Data was obtained from an operational Air Defence site based on live operations. Specifically, video and voice recordings were obtained from a number of Fighter Controllers during live operational sorties as identified during the preliminary survey. Post-task analyses were conducted with the Fighter Controllers to identify critical interaction points and to elicit suitable SA probe questions which were to be used during the Simulation Phase. Plot and track data recordings were also collected to assist with the development of high-fidelity simulations.

Simulation Exercise Phase

The plot and data recordings collected during the Scenario Development phase were used to generate realistic control scenarios based on the observed live operations. Simulations were then run in an operational environment using a number of Fighter Controllers for each different scenario. This phase provided both qualitative and quantitative data relating to the ICCS interaction design and the resulting product and processes of SA.

The initial findings of the UKADGE System Safety Study have already directed system developers to specify SA as a critical safety attribute for a replacement ICCS (18). Also, as a direct result of the safety study findings, the safety requirements for the replacement system now specify that the design must balance the requirements of both SA and usability in the design of human-machine system interactions (18).

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SUMMARY

This paper has made a case for Situational Awareness (SA) as a critical attribute for evaluating the safety of human-machine systems by quantifying the level of SA acquired through the system interactions. It was suggested that SA is a dynamic concept that exists at the interface between an operator and the environment. A pragmatic definition of SA was given as a measure of the degree of dynamic coupling between a system operator and a particular situation. A tangible benefit of this perspective of SA is the focus on the inseparability of situations and awareness. The Situated Cognition perspective of SA focuses attention on both what is inside the head (awareness from a cognitive perspective) and also what the head is inside (the situation which provides observable data). From this discussion, it is a contention of this paper that SA is a critical safety attribute that can be used in the context of human-machine systems to quantify the relative safety of a human-computer interface.

The paper has briefly presented aspects of a field-study of a military air defence system and introduced an Interactive System Safety Analysis Method for evaluating both the process and the product of SA in context. The initial findings of the field-study have already directed the developers to specify SA as a critical safety attribute for the replacement interface. The safety requirements for the replacement system also now specify that the replacement system must balance the requirements of both SA and usability in the design of interfaces and system interactions.

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