A situation awareness analysis scheme to identify deficiencies of complex man-machine interactions

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Abstract: This paper presents a scheme for a systematic study of deficiencies of support for situation awareness (SA). Current theories are not suitable to clearly define the required situation awareness (RSA) in complex man-machine interaction (MMI) contexts. Therefore, deficiencies of MMI are difficult to recognize and resolve. This paper analyses the limitations of current SA theories when they are used to study information intensive task environments. To overcome these limitations, the presented research proposes an explicit definition of RSA and provides a structured analysis scheme which allows researchers to gain a more holistic body of knowledge about SA. This scheme was applied in nautical traffic management context to identify current deficiencies of SA support. The observation is that approximately 80% of the identified deficiencies are related to how MMI supports human information processing. Future research will focus on informing to develop interface solutions which enhance operators' SA.

Keywords: man-machine interaction, situation awareness, analysis scheme, deficiencies, nautical traffic management, information intensive task environment, informing

1 Introduction

Within different divisions of Rijkswaterstaat (the Executive Body of the Dutch Ministry of Infrastructure and the Environment), operators control events and incidents in a particular region, and provide relevant information about the situation to skippers, colleagues and emergency services. They need to concurrently address (i) safe water levels, (ii) sufficient clean water, (iii) safe and efficient traffic flows, and (iv) availability of reliable and useful information. In the Netherlands, there has been an increase in the amount and complexity of traffic on waterways. Traffic will continue to increase in near future due to the extension of the Port of Rotterdam. The port area is growing by 20%. At the end of 2014, new terminals will be operational and the container capacity of the port will be doubled (Port of Rotterdam Authority, 2013; 2014). To manage the potential bottlenecks in waterway traffic, traffic management is shifting from local traffic control to corridor traffic management. While the focus is shifting to corridor traffic management, the operators still use information systems which were developed for local traffic control.

In nautical traffic management centres, operators need sufficiently complete and accurate situation awareness (SA) to support integrated water management. To gain and maintain their SA, operators simultaneously deal with several different information systems, such as geographic information systems, database management systems and electronic logbooks. While using traditional systems in the changed traffic situation, operators experience difficulty at gaining proper SA. To cope with the increasing amount and complexity of traffic on the waterways, Rijkswaterstaat aims to improve and unify working methods and responsibilities of nautical operational network management (ONM) tasks and wishes to redesign the man-machine interaction (MMI) to optimize task performance (Staveren and Arts, 2012).

To be able to redesign MMI related to traffic management tasks, Rijkswaterstaat should first identify deficiencies of current support of SA. Identification of deficiencies of SA support requires understanding of what it means when operators do not have proper SA. This implies the need for understanding required situation awareness (RSA). However current definitions of RSA mainly provide synonyms for RSA. They consider RSA as the information needs to achieve operators' goals (Endsley, 2012). This type of definition is difficult to apply in information intensive contexts. Furthermore, current SA theories disjointedly consider various individual, task and system factors as factors that have an influence on operators' SA. Deficiencies however are not necessarily related to a single factor. A deficiency related to task complexity for instance can be related to a lack of operators' training or experience. Or a task might be considered complex because the used system insufficiently support this task. Existing studies have paid limited attention to a holistic understanding of factors influencing SA to identify deficiencies of current support systems. To the best of our knowledge, no research has provided a method to explicitly consider information needs separate from RSA. To this end, we aim to supplement current SA theories with support for a systematic study of deficiencies of SA support systems in information intensive MMI context.

Section 2 presents the insights we have obtained from our literature review and discusses the limitations of existing SA theories when aiming to gain a holistic insight into SA. At the end of section 2, we provide a novel definition of RSA and we propose an analysis scheme for a structured study of SA. Section 3 presents how the definition of RSA and the proposed analysis scheme support the study of deficiencies of current support for SA in nautical traffic management context. The discussion in section 4 explores to what extent this contribution helps researchers to study situation awareness in information intensive situations. In conclusion, the article provides a summary, discusses implications of applying the analyses scheme and proposes directions of future research.

2 Situation awareness in traffic management and analogue contexts

Operator's SA is important in a broad range of command and control tasks. Consequently, the term 'situation awareness' is widely used in commercial and military aviation (Endsley, 1993; 1999; Wickens, 2002), air traffic control (Mogford, 1997; Niessen and Eyferth; 2001), process control (Kaber and Endsley, 1998; Patrick et al., 2006) and traffic operations (Roth et al., 2006; Wiersma, 2010). In the fields of aviation, air traffic control and process control various theories of SA have been developed. Endsley's theory, published in 1995, is by far the most commonly used (Rousseau et al., 2004; Salmon et al., 2007; Wickens, 2008). Endsley (1995, p.36; 2012, p.554) defines 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*".

SA theories developed in aviation, air traffic control and process control are considered generic across many different dynamic task environments (Endsley, 1995; Hogg et al. 1995). These theories are based on the assumption that SA is especially relevant in dynamic environments, where the state of the environment develops both with and without the operator's actions (Niesen and Eyferth, 2001; Wickens, 2002). Consequently, operators are dependent on an on-going up-to-date analysis of the environment (Endsley, 1995). A second important characteristic is that operators working in these environments typically pursue multiple goals simultaneously. To do so, they need to carry out multiple tasks, which are competing for an operator's attention and require time-constrained decisions and actions (Kaber and Endsley, 1998).

We argue that the nautical traffic management environment shares the above mentioned characteristics of a dynamic task environment. Operators need to pursue multiple goals simultaneously; they are responsible for (i) safe water levels, (ii) sufficient clean water, (iii) safe traffic situations, (iv) efficient traffic flows and (v) availability of reliable and useful information. These five main goals cannot be addressed separately, as they are interrelated. Time-constrained measures to ensure safe water levels, such as limiting the use of locks, for instance, can have a negative effect on safe and efficient traffic flows. Especially, it can happen if operators do not provide accurate information to the skippers in time. Operators' can take traffic management measures and/or provide information to the skippers to influence the traffic management environment to pursue their goals. The skippers' actions and the weather conditions however are unpredictable. Therefore, operators need to constantly monitor the controlled environment to maintain proper SA. In conclusion, current SA theories developed in aviation, air traffic control and process control contexts provide a useful framework for studying operators' SA in nautical traffic management context (Wiersma, 2010).

2.1. Situation awareness knowledge

SA is an umbrella term, encompassing independent pieces of information about the state of the dynamic environment as well as understanding of their relations. To simplify and structure the study of SA knowledge, a distinction in levels of SA, as proposed by Endsley (1995), is used:

Level 1 Perceptual knowledge: the cognitively unprocessed knowledge of elements in the current situation.

Level 2 Comprehended knowledge: a deeper understanding of the meaning and relationships of knowledge in the current situation.

Level 3 Projected knowledge: insight in future activities of the elements in the environment and understanding of future environment dynamics in relation to operator's goals.

Operators who successfully manage nautical operational networks understand the meaning and relationships of a large amount of pieces of information about the dynamic environment. This includes relatively static area knowledge and rather dynamic data and knowledge of waterways, locks, bridges, waterworks, ships and weather conditions. They for instance, among other things, know the cargo of a ship, the direction of the wind, the type of companies at shore and the relations between those in order to decide whether a ship can safely pass a fire at a company on shore. If an operator decides to close a waterway, he knows the locations of ships on the waterway and the availability of anchorage grounds to aid ships to find a suitable place to wait. Whether an anchorage ground is suitable depends on dimensions and cargo of the ship as well as on dynamic environmental conditions like water levels. Due to the large amount of required information, a main challenge lays in the ability of operators to locate and process the needed information (Endsley, 2000).

2.2. Situation awareness assessment

In traffic management and analogue contexts, operators remotely control the environment. They process input from information systems guided by mental models, a set of knowledge which forms a conceptual analogue of the external world to understand and predict the environment, for SA assessment (Mogford, 1997). SA is the foundation for their decision making and actions, which influence the state of the environment (Endsley et al., 2006). If the gained SA knowledge conflicts with the applied mental models, this can trigger operators to update their mental model (Yin and Laberge, 2010). Figure 1 shows a schematic description of SA assessment in remote control context. Traditional information systems mainly support perception of pieces of information. More advanced or context-aware support systems use computational SA assessment to directly support comprehension of the situation, to provide projected SA knowledge or to provide decision support to the operators (Dey, 2001; Essendorfer et al., 2009; Feng et al., 2009; Goossens et al., 2004).

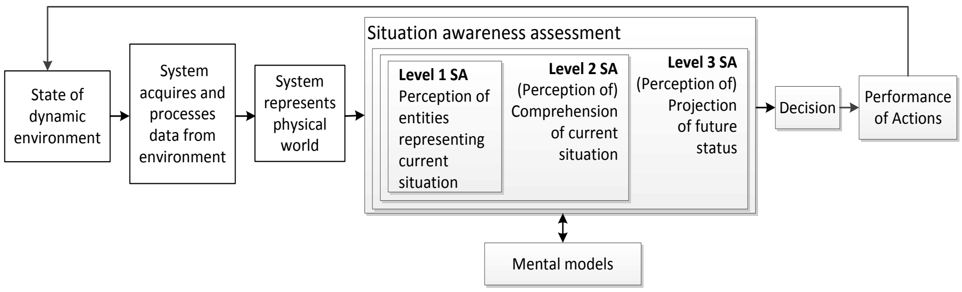

Figure 1 Model of SA assessment, developed based on Figures 1, 3 and 4 of Endsley (1995)

SA assessment is influenced by many individual factors such as operators' abilities, attention, working memory capacity, experience, training, information processing mechanisms, goals, and expectations (Adams et al., 1995; Durso and Sethumadhavan, 2008; Endsley, 1995; Patrick and Morgan, 2010). Existing studies have primarily addressed the influence of individual factors on SA separate from other influential factors. Whether individual characteristics however negatively influence an operator's SA depends on task and system factors as well. For instance colour blindness negatively influences an operator's SA only if the system interface uses colour coding which colour blind people are unable to distinguish.

Task complexity, stress, workload and automation are considered as task factors which influence SA assessment (Endsley, 1995; Kaber et al., 2006; Wickens, 2002). Endsley (1995) and Wickens (2002) argued that a higher task complexity will increase the amount of mental workload required to gain and maintain SA. They consider a high mental workload as a stressor, while Endsley reasoned that stress reduces working memory capacity and negatively influences SA assessment. Under stress, operators tend to only focus on a limited number of dominant pieces of information. However, it depends on the systems used to retrieve information which information they focus on. And thus to which degree the working memory decrements affect SA. Automation can be used to relieve operators from a part of the workload, but it can also result in a loss of operators' SA due to human-out-of-the-loop problems (Kaber et al., 2006). Apart from this, a low mental workload can lead to vigilance problems (Endsley, 1995; Wickens, 2002). Current theories mention these correlations, but they address the different task and system factors influencing SA separately. The 'at-the-first-sight-clear' breakdown of distinct factors does not support a structured study of SA. It has been our assumption that addressing factors such as stress, workload and complexity isolated from each other, and from the systems used, will not give a proper insight into the effects that these factors have on the operator's SA.

2.3. *Required situation awareness*

Only if RSA to achieve operators' goals is properly specified, examination of higher or lower degrees of SA or loss of SA is meaningful. Current SA theories define RSA as the information needs associated with operator' goals. They consider individual, task and system factors as factors that influence SA, but not as factors that have an influence on RSA. For example, Endsley (2000; 2012) analysis RSA without considering aspects of technologies. Consequently, defining RSA using the current theories implies defining RSA as all information that is needed by the operator to realize the goals. If all pieces of the necessary information are considered a part of RSA, than they all have to be memorized. This type of definition is difficult to apply in information intensive contexts. It does not support understanding of how to make a large amount of information available to the operator. Besides, it oversimplifies the evaluation of SA support systems. Following this definition would conclude that the more information an operator memorizes, the better the system supports SA. In case of systems for information intensive tasks, a suitable system however may do much more than just providing support for an operator to memorize pieces of information. Instead, a suitable system will minimize the amount of information which operators need to continuously reason with and memorize to reach operators' goals. This can be illustrated by the following example.

> Imagine two operators, working with different man-machine interfaces. In case of a breakdown of a lock, they need to provide information to others, such as skippers, colleagues and emergency service. They for instance inform skippers about the expected queue time of a lock on an alternative route. Thus, skippers can decide whether it is wise to take the alternative route. Imagine an information system whose interface constantly displays the characteristics of all locks and a list of detailed information about all ships and the coordinates of their position in the waterway. With such a system, all data is available. It however is mentally demanding for an operator to decide upon the queue time of the lock. The operator needs to search for relevant pieces of information and understand their meaning and relations to predict the time it takes to transfer all waiting ships. The relevant information is not sufficiently accessible to the operator. It will take too long to recalculate the relevant queue time each time when someone requests this information. In order to be able to respond in a timely matter, information about the related ships, the lock and queue time are part of his RSA. For an operator using a context-aware system which automatically displays the relevant queue times of locks while hiding irrelevant data, accessing this information is not mentally demanding and takes a short time. Due to the moderate effort that it takes to access this information, he most likely will process information differently. Detailed pieces of information which are only required to calculate the queue time do not have to be known. Therefore, they are less likely to be part of the operator's SA. This however does not mean that this operator has a lack of SA.

As this example illustrates, understanding criteria for proper SA requires viable understanding of the interaction between the operators and their task environment (Smith and Hancock, 1995). In nautical traffic management and analogue contexts the goals of operators are related to a remotely controlled task environment. Therefore, insight in MMI is essential to specify RSA. The man-machine interface structures the distribution of information between systems and operators and influences operators' information processing for SA assessment (Mogford, 1997; Patrick and Morgan, 2010; Stanton et al., 2006; 2010). We therefore claim that the difference in the man-machine interface influences RSA. In conclusion, we propose the following definition of RSA.

Required situation awareness is the relevant information about the dynamic environment which operators need to have constantly mentally available during task performance, where relevancy depends on goal *dependent information needs and the interaction between goals, tasks, individual factors and system factors.*

In line with this definition we propose an analysis scheme to study SA, see Figure 2. The novelty of this scheme is that it supports researchers to explicitly consider the distinction between information needs and RSA. Besides, the proposed scheme differs from those implied by the existing theories on SA in that it concurrently considers the three influential factors of SA, namely; (1) the individual operator related factors, (ii) system factors, and (iii) task factors, as factors which jointly influence MMI (Doorn et al., 2014).

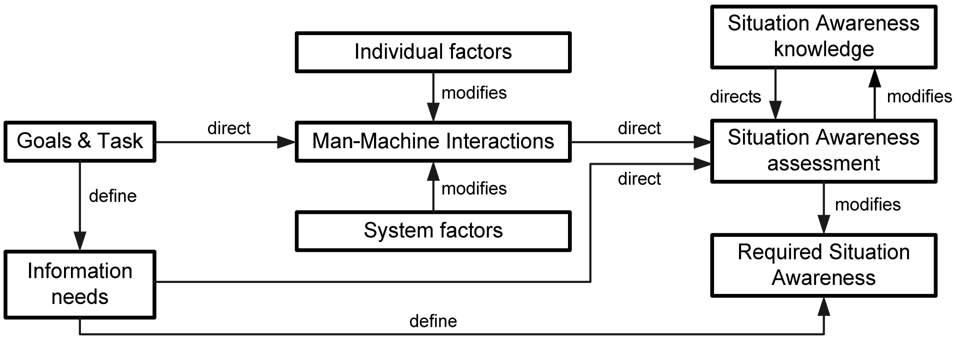

Figure 2 Analysis scheme to study situation awareness in a holistic matter (Doorn et al., 2014)

3 Application of the analysis scheme in traffic management context

The motive for our attempt to supplement current SA theories with support for gaining more holistic knowledge of SA was to structure our study to identify deficiencies of current support for SA in information intensive task environments. In this reported research, we have applied the analysis scheme in a case study focusing on a nautical traffic management situation. Figure 3 provides an overview of the methods used.

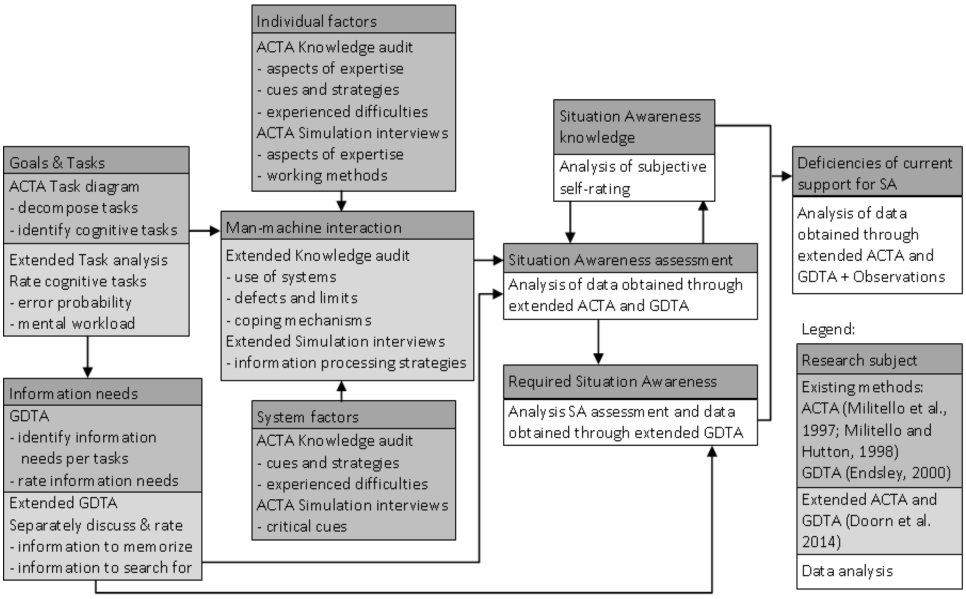

Figure 3 Overview of methods used to apply the analysis scheme in a practical case study

3.1 Insight in SA for ONM

To gain insight in goals, tasks and information needs, a total of 22 nautical traffic management operators and eight subject-matter experts were involved in task analysis sessions (Doorn et al., 2014). Firstly, operational goals were listed. For each goal, the related tasks, subtasks and activities were defined. Lastly, information needs per activity were derived. Table 1 gives an overview of all the identified tasks and subtasks for operational network management.

Table 1: Tasks and subtasks of ONM

Tasks	Sub-tasks
Assess traffic conditions	Locate/identify shipping
	Follow shipping
	Observe network
	Register information
Inform stakeholders (skippers, emergency services and colleagues)	Provide traffic information
	Provide information in case of restrictions
Manage incidents	Take active actions for incident management
Plan traffic measure (planned restrictions)	Determine impact (planned restrictions)
Plan traffic measure (unplanned restrictions)	Determine impact (unplanned restrictions)
	Prepare traffic measure (unplanned restrictions)
Set / release traffic measure (planned and unplanned restrictions)	Take actions to remedy limitations and to effect traffic measures
	Set traffic measures
	Lift traffic measures
	Register information

The 22 operators participated in a session to discuss cues and strategies which operators use to reach ONM goals. They individually rated the identified information needs on two aspects on a scale of 1 (not important) to 5 (very important):

- Importance of searching for this information during the task, although afterwards it can be forgotten (indicated as ‘Seek’ in Figure 4).
- Importance of memorizing this information, to make it part of one’s situation awareness (indicated as ‘RSA’ in Figure 4).

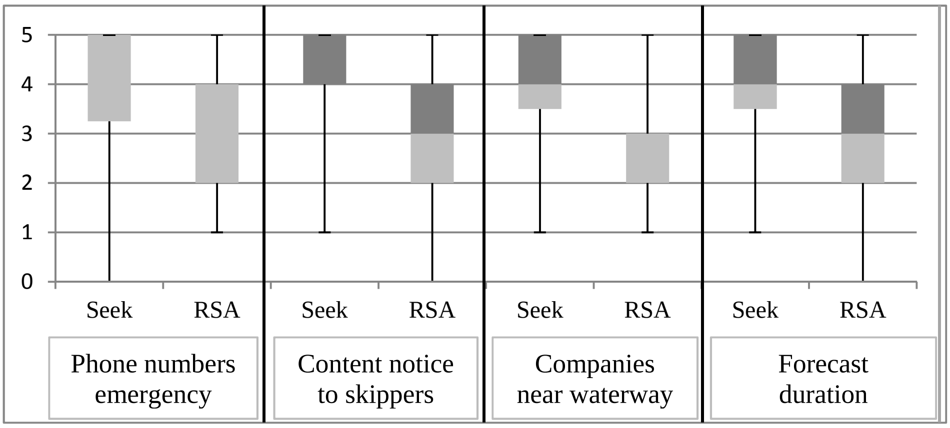

Figure 4 Ratings of information needs

Operators considered (i) ‘Waterway network overview’, (ii) ‘VHF channel of call’, (iii) ‘Position malfunctioning objects’, (iv) ‘Location objects’, (v) ‘Ship names’, (vi) ‘Shipping intensity near objects’, and (vii) ‘Estimated location of VHF call’ as the main elements of ONM RSA. The main information needs which operators need to access, but afterwards may forget, are (i) ‘Phone numbers emergency services’, (ii) ‘VHF channel of call’, (iii) ‘Content notices to skippers’, (iv) ‘Companies near waterway, (v) ‘Forecast duration restrictions’, and (vi) ‘Phone numbers phone calls’. Figure 4 shows the difference in ratings for the four information needs which are considered of main importance to access, but which are not considered of main importance to be included in RSA.

3.2 Deficiencies of current support of SA for ONM

The data gathered while applying the proposed analysis scheme in ONM practice, as visualized in Figure 3, was analysed to identify deficiencies of current support of SA for ONM. In total, more than 100 deficiencies were identified, which we could cluster into 29 dissimilar deficiencies. Approximately one-third of the deficiencies are directly related to informing; e.g. the nature, processes, and design of systems used to inform operators on their environment. Some deficiencies in this list have a cause and effect relation. Taking these relations into consideration, circa 80% of the deficiencies is related to how the current system interfaces support human information processing. These deficiencies can be clustered into four main groups, see Table 2.

Table 2: Deficiencies of current support for ONM

Deficiencies	Related causes	Related effects
Deficiencies due to insufficient quality of information	Insufficient quality of information in systems	Operators require large amount of information
	Some information is subject to change	
	Required information of others unreliable	
	Operators require large amount of information	
Deficiencies due to relation between difficulty to access information and large amount of information	Required system not fully functional or available	Insufficient quality of information in systems
	Some information is required sporadic	Current information presentation puts high demands on operators’ ability to keep overview of a large area of control
Deficiencies due to current information presentation puts high demands on operators’ ability to keep overview of a large area of control	Operators require large amount of information	ONM operators take wrong or no timely action
	Difficulty to access relevant information	
	Some information is only available in operator's mind	
	Operator receives no direct feedback on own actions	
	Time component of information not supported by systems	
Deficiencies due to operators miss, forget or skip relevant actions	Operator receives no direct feedback on own actions	
	Time component of information not supported by systems	
	Mental workload exceeds operator's mental capacity	
	ONM operators are exposed to stressful situations	
	ONM requires to pursue multiple tasks simultaneously	
	ONM operators do not follow a uniform working method	
	ONM goals do not all receive the required amount of operator's attention	
	ONM actions have far-reaching consequences	
	Criticism about work of civil servants limits freedom of actions	
	System does not support efficient workflow	

4 Discussion

The aim of our research was to develop a structured approach to study deficiencies in support of SA in information intensive task environments. We argued that current SA theories, which consider RSA as all information needed by operators to fulfil their goals, are not suitable to understand SA for information intensive tasks. Besides, they do not simultaneously consider the different aspects which influence SA. Our main objective was to develop a definition of RSA and to structure the logic behind this definition in an analysis scheme to gain more holistic knowledge of SA in information intensive task environments.

This research work contributed a novel definition of RSA, which proposes a clear distinction between RSA and information needs. Our case study confirmed the usefulness of this distinction. Prior to our study, operators referred to all available pieces of information as highly relevant for SA. As visualized in Figure 4, sessions based on the proposed analysis scheme helped operators to make a distinction between the importance to be able to access pieces of information and the importance to have pieces of information as part of RSA. Some pieces of information, such as phone numbers and the content of notices to skippers, are considered highly important in terms of accessibility, but are considered less significant when talking about RSA.

For the proposed analysis scheme to be valuable and valid, it needs to be applicable in real-life research to gain insight in deficiencies in support of SA. In our earlier research work, we provided rational reasons to scrutinize the logical stand of our theory and analysis scheme. We argue that (i) the reasoning model is well-grounded to be logical, (ii) it does not have any internal inconsistence or incoherence, and (iii) it does not suggest illogical consequences when applied (Doorn et al., 2014). This research work presented a case study which verifies that the analysis scheme helps to identify deficiencies of current support for SA which are related to informing.

It was our expectation that a substantial part of the deficiencies of current support for SA are related to interface design. Approximately 80% of the deficiencies which were identified in our case study are indeed related to how MMI supports human information processing. Evaluation of the four main groups of deficiencies, as presented in Section 3.2, with eleven subject-matter experts supports this expectation. The experts indicate that it is impossible to reach a situation where all data is available and correct. It is more the question of how to deal with missing or incorrect information, instead of how to prevent this from happening. Missing information due to insufficient logging of incidents however is seen as a potential area where a higher quality of information can be reached through the use of improved interface design of electronic logbooks. The subject-matter experts consider it logical to focus on interface design when addressing the deficiencies of how to access large amount of information and how to support operators' overview of a large area of control. The deficiency cluster of different reasons why operators to miss, forget or skip relevant actions, according to the experts, is partly related to operators' attitudes and habits. The experts however believe that interface design can help to prevent situations where operators do not carry out all relevant tasks. They mentioned a digital checklist or progressive scheme as possible solutions. In conclusion, the case study confirms that the proposed analysis scheme is suitable to structure the study of deficiencies of support for SA in information intensive task environment.

5 Conclusion

This paper has presented a definition of RSA, which emphasises that operators' RSA depends on goal dependent information needs and the interaction between goals, tasks, individual factors and system factors. We have presented an analysis scheme which structures the study of SA. The definition and analysis scheme help differentiate RSA from information needs. Defining information needs per activity is a time consuming task, but is necessary to understand RSA. The proposed analysis scheme offers a structured approach to study deficiencies of current support for SA in information intensive task environments, but is less suitable for gaining a quick first insight in SA.

Approximately 80% of the deficiencies which were identified in our case study were related to human information processing. Experts recognized the identified deficiencies and considered them to be the most potential points for improvement to overcome current risk of lack of operators' SA. These results indicate that interface design to enhance informing for SA assessment is a potential direction for our aim to overcome the experienced difficulty at gaining proper SA.

Application of the presented analysis scheme in practice showed that pieces of information which are considered of main importance for operators' RSA are different from those pieces of information which are considered of main importance to be able to access. This finding raises the question whether designers should use different design solutions to visualize information which is part of RSA than that they should use to support the accessibility of information which is not part of RSA. We aim to address this question in our future research efforts, which will focus on developing interface solutions to enhance operators' SA.

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