Distinguishing Three Accounts of Situation Awareness based on their Domains of Origin

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Distinguishing Three Accounts of Situation Awareness based on their Domains of Origin

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Review of the literature reveals that different treatments and applications of situation awareness (SA) theories and measures often include reference to, or verification from, specific domains. This leads to the postulate that the application domain from which a conceptualization of SA arises plays a fundamental role in that conceptualization. To test this postulate, we compare SA accounts originating from three different domains - aviation, military command and control, and process control. The comparison of the three SA accounts illustrates that the domain of origin can have significant influence on the fundamental characterization of SA. In particular, the choices for the research paradigm in psychology, cognitive components (e.g., metacognition), orientation of time, and scaling of time can be partly traced back to properties or operator challenges specific to the domains of origin. Our comparison demonstrates that domain properties must be carefully examined for conceptualization and application of the SA notion.

INTRODUCTION

Situation awareness (SA) has been introduced as a dimension of human performance in almost every domain of human factors practice. Yet, despite two decades of research and use in practice, there is no consensus either on a theory/model of SA or on SA measures (e.g., Jeannot, 2000; Rousseau, Tremblay, & Breton, 2004; Salmon et al., 2008). Understanding this lack of consensus appears important for SA research. In particular, knowing the underlying factors motivating different conceptualizations of SA can improve the assessment of the implications for adopting specific SA accounts to develop operator support and measurement tools.

Review of the literature indicates that different treatments and applications of SA theories and measures often include reference to, or verification from, specific domains (see e.g., French, Matthews, & Redden, 2004; Golightly, Wilson, Lowe, & Sharples, 2010; Hogg, Follesø, Volden, & Torralba, 1995; Jeannot, Kelly, & Thompson, 2003; Salmon, Stanton, Walker, & Green, 2006). Domain properties, therefore, could be one of the underlying factors contributing to the diverse accounts and measures of SA. That is, the application domain from which a conceptualization of SA arises appears to play a fundamental role in that conceptualization. This postulate – that the domain origin influences SA conceptualization – has two serious implications for research on, and applications of, the SA notion. First, developing or adopting specific SA accounts for applications and measures should be based on mapping domain and task properties to psychological constructs, and NOT vice versa. Second, SA accounts that prioritize domain and task properties (i.e., situational factors) over psychological constructs should provide more precise guidance for design and measure for the application domain, but at the expense of generalization. In other words, the overlap of the SA notion between domains might not be sufficient to warrant generalization without substantial loss in utility for design and measurement.

To shed light on the significance of domain properties in conceptualizing SA, we compare SA accounts originating from three different domains - aviation, military command and control, and process control. The comparison illustrates how domain properties are relevant not only to the surface features (e.g., difference in parameters) but also to the fundamental characterization of SA.

SA CHARACTERIZATIONS

We begin by summarizing the SA accounts for aviation (Endsley, 1995), military command and control (Bryant, Lichacz, Hollands, & Baranski, 2004), and process control (Lau, Jamieson, & Skraaning Jr, 2012b).

Aviation – Endsley (1995)

Endsley (1995, 2000) applies the information processing model (e.g., Wickens, Hollands, Parasuraman, & Banbury, 2012) to conceptualize SA with three levels: Level 1, perception of elements in the environment; Level 2, comprehension of those elements; and Level 3, projection of those elements in the future. The three levels of SA form a descriptive model of SA intended for multiple domains (Endsley, 1995, p. 36). Though presented as a domain-general account, the three levels of SA are derived from the practical needs of the aviation domain (Endsley, 2004).

Endsley does not describe the three levels of SA much further beyond the literary definitions presented above, although she provides some brief examples of the three levels of SA for several domains such as power plant and military systems. She also discusses many other cognitive processes and performance constructs in the information processing model in relation to her descriptive SA model from general human factors perspective. For further details, refer to descriptions and critiques on this most frequently cited descriptive model of SA (e.g., Endsley, 2004; Jeannot, 2000; Rousseau et al., 2004).

Military Command and Control – Bryant et al (2004)

Bryant et al. (2004) develop the Critique, Explore, Compare and Adapt (CECA) Loop, a descriptive model

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composed of four phases of situation assessment and decision making specific to military command and control. A military plan triggers the CECA Loop by initiating the formulation of a conceptual model that depicts the ideal state of the battle space. The conceptual model prompts the iterative development of a situation model depicting the current state of the battle space. The conceptual model also formulates the structure and content requirements for the situation model to compare the current to ideal state of the battle space. The formulation and development of the situation model is called the *Critique* phase. With the structure and content requirements specified, the situation model guides information gathering and filtering to model the actual situation. The information gathering and filtering guided by the situation model is called the *Explore* phase. Given required information collected, the situation model is populated or updated with content. The populated situation model is thus the awareness of the situation that enables comparison with the conceptual model. Consistencies between the two models indicate effective progress of the battle plan (i.e., towards the military objectives), whereas inconsistencies suggest flaws in the conceptual model (i.e., expected outcome from actions according to the battle plan). The comparison between the two models is called the *Compare* phase. With the discovered inconsistencies between conceptual and situation model, military commanders respond accordingly, potentially involving changes to strategies and/or goals. Resolving or responding to inconsistencies between the conceptual and situation model is called the *Adapt* phase. The resolutions to the inconsistencies lead to a new conceptual model. So, following the adapt phase, the CECA loop iterates starting with the critique phase until termination of the military plan.

Like the three levels of SA, the CECA Loop does not include extensive description of the knowledge components (i.e., conceptual model, situation model and information gathered).

Process Control – Lau et al. (2012b)

Lau et al. (2012b) formulate components of SA as *knowledge products* of monitoring, diagnosis and self-regulation that comprise the key situation assessment activities of control room operations in process plants. Their literature review indicates that process plant monitoring is dominated by active search for information, as opposed to passive discovery of deviations; hence, the resulting SA is defined as the recognition of deviating processes that require operator attention. Diagnosis is dominated by the creative application of system knowledge or mental representations, as opposed to mechanistic processing of plant indicators; hence, the resulting SA is defined as the recognition of control needs of the process plant as well as the explanation of any process anomalies. Self-regulation is dominated by introspection of their own cognitive activities in affecting the plant operations; hence, the resulting knowledge is defined as the recognition of the need for adapting situation assessment and control strategies.

Lau et al. further construct an analogy between situation assessment and awareness in process control and problem solving research. The analogy highlights the resemblance between the cognitive challenges faced by operators in acquiring SA and by people in solving insight problems. Specifically, monitoring is analogous to identifying the structural properties and integrity of insight problems; diagnosis to iterative representation of problem spaces based on structural properties; and self-regulation to the cognitive adaptation to unsuccessful problem solving attempts (see e.g., Davidson, Deuser, & Sternberg, 1994; Kaplan & Simon, 1990; Kershaw & Ohlsson, 2004; Knoblich, Ohlsson, Haider, & Rhenius, 1999). Unlike Endsley and Bryant et al., Lau et al. focus on describing situation assessment and awareness in the context of process control with limited discussion on the interactions between the components or the relationships with other cognitive constructs.

DISTINGUISHING THE THREE CHARACTERIZATIONS

The three accounts share two basic tenets of the SA notion. First, each account depicts the knowledge products of human activities that are believed to be essential for making decisions about subsequent control actions. Second, the focus of these knowledge products is specific to the operating circumstances or "dynamics of the situation" as opposed to "static knowledge" (Endsley, 1995, p. 36). In summary, the three SA accounts are separate attempts of representing "knowing what's going on".

The three SA accounts also exhibit substantial differences. These differences can be attributed in part to the domain origins of each account. Thus, some SA accounts might reasonably be expected to be more useful for understanding operator cognitive work in one setting over another. To illustrate how these differences might be attributable to their domain origins, we compare the three SA accounts according to: (i) the nature of the problem space, (ii) reliance on metacognition, (iii) orientation of time, and (iv) scaling of time. The comparison reveals that the differences can influence SA research in terms of how researchers leverage psychology research, develop measures and transfer findings across domains.

Problem Space

The three SA accounts resemble different psychology or human factors research paradigms. The difference in research paradigms between the SA accounts can be attributed to the difference in engineered processes across domains.

Aviation systems commonly discussed in SA research are generally comprised of a single process of managing vehicle traffic, the control dynamics of which vary according to external demands. For such single-process, externally driven systems, controllers and pilots can rely on a single representation of the problem space – the time-space representation – to search for and interpret indictors of the situation. The essential challenge to acquiring SA in the aviation domain is the comprehensive and efficient processing of indicators within the given geographical boundaries according to external traffic demand. From this perspective, the information processing paradigm (e.g., Wickens et al., 2012) provides an effective basis to conceptualize SA for the aviation domain (see Bryant, 2003). Endsley's three levels of SA, which originate from the study of perception-control tasks in aviation, are built on the information processing model.

Military command and control systems function on both system- and mission- based processes, many of which are ill-defined. For instance, there are no laws (i.e., system knowledge) governing enemy responses to military actions. In fact, the military sometimes uses the term "intelligence" instead of "knowledge". Intelligence generally lacks an objective basis for evaluation. The value (or "truth") of the intelligence (e.g., tactics of the enemy) can only be assessed in hindsight. On the other hand, system knowledge generally connotes an objective basis for evaluation. For instance, the flying envelope of a fighter jet is given by the design specifications or determined by engineering principles. For this reason, the central challenge to acquiring SA in the command and control domain is constructing and modifying a representation of the problem space for gathering intelligence in real-time and highlighting action opportunities to advance mission objectives. From this perspective, the ill-defined (see e.g., Schraw, Dunkle, & Bendixen, 1995) and complex problem solving (e.g., Frensch & Funke, 1995; Sternberg & Frensch, 1991) paradigms provide some foundation to conceptualize SA for the military command and control domain. Reflecting the ill-defined nature of the system, the CECA Loop specifies the *conceptual model* as a component to emphasize the constructivist nature in military command and control.

Process systems are comprised of many engineered processes, designed for steady state operations and shielded from external disturbances. For such closed, multi-process systems, operators extensively apply system knowledge to formulate the problem space to effectively direct search for (i.e., monitoring), and guide interpretation of (i.e., reasoning about), indicators. In essence, the central challenge to acquiring SA in process control is effectively formulating the problem space through creative and selective application of system knowledge. From this perspective, the insight problem solving paradigm provides an effective basis to conceptualize SA for the process control domain (Lau et al., 2012b). (For a discussion, also see Skraaning Jr. et al., 2007.)

Metacognition

A second salient difference between the three SA accounts is their varying emphasis on metacognition. For the variety of perception-control tasks in aviation, the time-space representation of the system appears sufficient for controllers and pilots. Thus, problem formulation or re-representation is practically unnecessary. Metacognition is virtually absent in Endsley's model and more broadly in SA in aviation (e.g., Jeannot et al., 2003; Mogford, 1997).

The CECA Loop for command and control includes a conceptual model as a component to emphasize the constructivist nature of SA and the demand for metacognition in the domain. Further, the Adapt phase is outlined as the process to reformulate the conceptual model, implying knowledge from continual assessment and regulation of cognitive strategies.

Operating process plants often involves problem formulation for representing the process systems in a manner that can lead to accurate interpretation of the indicators and selection of control actions. According to insight problem solving research and process control field studies, metacognition appears critical to successful problem formulation. Lau et al. (2012b) specify self-regulation and recognition for adaptation of cognitive behaviors to reflect such metacognitive activities. While self-regulation and recognition for adaptation in process control may bear some resemblance to the conceptual model in military command and control, the nature of problem formulation or representation differs between the domains. Specifically, a process plant operates on a relatively complete design with a comprehensive set of engineering specifications; whereas, a military force operates on a partial design with many underspecified behavioral characteristics of the opponents and environmental characteristics of the battlefields.

Orientations of Time

A third difference between the SA accounts lies in their temporal orientations. These orientations reflect the control requirements for the engineered processes or operations of the domain. In other words, the dynamics of the processes determine the temporal orientation of the workers.

The aviation domain relies on controllers and pilots to avoid collisions. As suggested by the three levels of SA, controllers and pilots orient towards the present and near future because directing and responding to traffic inherently requires knowledge of the current and future status of aircraft in the surrounding. The reliance on a single representation allows for relatively precise prediction of various indicators to be realistically achievable by controllers and pilots.

The military domain relies on commanders to direct and control resources to achieve mission objectives, which can vary drastically across missions. Given highly variable control requirements, the CECA Loop does not suggest any dominant or systematic temporal orientation. The open and constructivist nature of the domain likely prohibits detailed examination of commander's temporal orientations, distinguishing military command and control from other domains including aviation and process control.

An interesting point of discussion is that Bryant et al. (2004) substitute "adapt" in the CECA Loop for "project" in Endsley's model. Military forces face opponents who exhibit creative and adaptive behaviors. The creative actions and reactions between the opposing forces lead to an extremely open system. Consequently, "projection" or the time orientation towards the future as defined by Endsley may not be applicable to command and control because every action could potentially change enemy behaviors. As a result, prediction without accounting for one's actions would have limited utility (e.g., game of chess), even though Bryant et al. (2004) did not dismiss projection in their comparison between the CECA Loop and Endsley's three levels of SA. In a subsequent military command and control empirical study, Lichacz (2008) omitted Level 3 SA queries citing the dependency of future events on courses of actions chosen by participants. In summary, adaptation connotes commander behaviors more accurately than projection given the open nature of military command and control.

Process plants rely on operators for production, compensatory and corrective control actions, sometimes to transition between plant states and often to maintain optimal, steady-state operations. During diagnosis, process operators orient towards the present and future for production control; the present and immediate future for compensatory control; and the past for corrective control (Lau et al., 2012b). This shift in temporal focus according to control needs is important for SA. For instance, precise prediction of process parameters is often meaningless during steady-state operations and becomes unrealistic during abnormal operations prior to the diagnosis of a major operational disturbance. On the other hand, knowledge of past events often supports diagnosis of process faults that disturb steady-state operations. This contrasts with controllers and pilots who are rarely concerned about past events, the knowledge of which provides limited utility in handling traffic to avoid collisions.

Scaling of Time

In addition to the differing orientations of time, the three SA accounts specify different time scales to reflect work behaviors in adaptation to domain properties.

For much of the SA literature on aviation that focuses on managing traffic, pilots and controllers think in absolute time corresponding with the time-space representation. In this case, an absolute time scale supports precise communication across multiple system actors (i.e., pilots and air traffic controllers) that inherently fit into the traffic control process.

In military command and control, the CECA Loop specifies “conceptual” time to reflect the constructivist nature of command and control (Bryant et al., 2004, p. 113). Commanders construct time scales according to the demands and objectives of the mission.

Process operators often think in “process” or “action” time with respect to their representations of plant processes to inform control actions (also see Cara & Lagrange, 1999; de Keyser, 1987). A time scale connected to the process behaviors and conditions is more useful than a precise, absolute scale.

DISCUSSION

The comparison of the three SA accounts illustrates that the domain of origin can have significant influence on the fundamental characterization of SA. In particular, the choice of research paradigm in psychology, cognitive components (e.g., metacognition), orientation of time, and scaling of time can be partly traced back to properties or operator challenges specific to the domains of origin.

Recognizing that domain properties could result in fundamentally different SA accounts has deep implications for SA research and application. The three SA accounts adopt different psychological research paradigms to depict the cognitive challenges specific to their domains of origin. Researchers cognizant of the research paradigm applicable to a specific domain could leverage theoretical, empirical and methodological insights already existing in the literature. Further, as every research paradigm entails assumptions, the identification of the embedded research paradigm in any SA conceptualization could also alert researchers to potential bias. In other words, the perspective on SA can change significantly according to domain.

As a consequence of different research paradigms, the SA accounts consists of different components. The process control, and military command and control SA accounts include a metacognition component, whereas, Endsley’s aviation-derived SA account does not. Further, the nature of metacognition between the process control and military command and control is significantly different. This suggests that an SA account suitable for one domain might emphasize irrelevant aspects of human cognition and neglect critical operator behaviors for another domain.

Different characterizations across the SA accounts also motivate development of different measures to collect data relevant to operator SA. For instance, interface support and SA measures may focus on projection in aviation but metacognitive activities of problem formulation in process control. Individual domains likely need to establish research programs and design goals concerning SA that are specific to the cognitive demands imposed on their operators. Otherwise, abstract constructs found in some SA accounts can be misleading when applied in some work settings.

The, aviation, military command and control, and process control SA accounts indicate different temporal orientations, which constitute an important sub-dimension of SA. To account for the differences within the same sub-dimension of SA, research questions and interface design strategies concerning SA may need to differ across domains. For temporal orientation, practitioners may present past information with trend graphs for process operators but expected events with predictive displays for air traffic controllers. In summary, the same aspects of SA may deserve different consideration and investigation across domains.

Further, the SA accounts adopt different time scales to suit the operational situation. Aviation adopts clock time; process control adopts action time; military command and control adopts conceptual time. Knowledge on how operators psychologically scale time or other physical dimensions can support interpretation of empirical results and development of measurement tools. Further, practitioners may design interfaces with scales that are compatible with those of the operator in particular domains.

FUTURE WORK

The article compares only three SA accounts and a few respective empirical studies to highlight the influence of domain origin. Future work will extend this comparison analysis in three ways. First, the scope of analysis needs to include a larger portion of the literature, which contains several qualitative SA accounts and many empirical studies for individual domains. Second, the analysis needs to include comparison of measures, which can have major impacts on the development and understanding of individual SA accounts. It is important to learn how some measures, especially domain dependent ones, might enable or limit the generalizability of SA. Third, the comprehensive analysis should lead to a set of principles or a formal method for matching domain properties to particular psychological theories or SA accounts to support design and measurement.

CONCLUSION

Our review supports the assertion that the application domain from which a conceptualization of SA arises plays a fundamental role in forming that conceptualization. The differences stem from practical necessity to focus on specific operator needs in individual domains, thereby influencing the characterizations and measures of SA. Thus, properties and operator challenges specific to individual domains should not be considered surface features but rather essential characteristics in SA research.

The impact of domain-specific properties and operator challenges on SA characterization has deep implication for application as well. Domain-specific examination of SA can provide useful guidance for selecting, developing or employing SA measures with improved sensitivity, reliability and validity (see e.g., Durso, Bleckley, & Dattel, 2006; Hogg et al., 1995; Lau, Jamieson, & Skraaning Jr, 2012a; Lau et al., 2011). Similarly, domain-specific SA characterizations can inform the design of interfaces with improved compatibility to the operator work. In other words, developing applications to improve or measure operator SA in industrial settings cannot solely rely on an abstract accounts that may assume unimportant features from the originating domains and exclude critical details for the application domain.

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