ERGONOMICS, 2016
VOL. 59, NO. 7, 976–988
http://dx.doi.org/10.1080/00140139.2015.1100329

Situation awareness acquired from monitoring process plants – the Process Overview concept and measure

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ABSTRACT
We introduce Process Overview, a situation awareness characterisation of the knowledge derived from monitoring process plants. Process Overview is based on observational studies of process control work in the literature. The characterisation is applied to develop a query-based measure called the Process Overview Measure. The goal of the measure is to improve coupling between situation and awareness according to process plant properties and operator cognitive work. A companion article presents the empirical evaluation of the Process Overview Measure in a realistic process control setting. The Process Overview Measure demonstrated sensitivity and validity by revealing significant effects of experimental manipulations that corroborated with other empirical results. The measure also demonstrated adequate inter-rater reliability and practicality for measuring SA based on data collected by process experts.

Practitioner Summary: The Process Overview Measure is a query-based measure for assessing operator situation awareness from monitoring process plants in representative settings.

ARTICLE HISTORY
Received 22 April 2014
Accepted 21 September 2015

KEYWORDS
Situation awareness; process control; monitoring; domain-specific; measurement

Introduction

Situation awareness (SA) is an essential part of human performance in process control (e.g. Burns et al. 2008; O'Hara et al. 2012; Tharanathan et al. 2010). The SA notion, which refers to 'knowing what is going on' (Endsley 1995b), makes explicit that the coupling between situation and awareness/cognition is important for effective decision-making and control (e.g. Endsley 2004; Jeannot 2000; Rousseau, Tremblay, and Breton 2004; Stanton et al. 2010). This coupling implies that the nature of awareness is intrinsically linked to properties of both the situation and operational environment, assuming a triadic semiotic perspective that emphasises the interaction between situation and awareness (Flach 2015). Hence, SA offers distinct utility in comparison with other human performance notions that assume a dyadic semiotic perspective focusing on particular aspects of awareness, such as workload and trust (e.g. Flach 1995; Flach and Rasmussen 1999; Rousseau, Tremblay, and Breton 2004).

In process control, many past monitoring and diagnosis studies examined how operators sought information about the equipment and process to make control decisions (e.g. Edwards and Lees 1974). These studies typically included descriptions of specific contexts and plant processes managed by the operators. When the SA notion became part of the scientific terminology, the literature shifted from the language of monitoring and diagnosis to SA. Hogg et al. (1995), and Kaber and Endsley (1998) discussed the general relevance of the SA notion in process control. Both adopted the most prominent SA account – Endsley's three levels of perception, comprehension and projection (1995b). Their descriptions suggest that operating a plant safely and efficiently depends on operators accurately perceiving parameters of the process, interpreting those parameters to learn about the operating states and predicting trends of the process parameters.

The prominence of the three-level SA characterisation may be attributed to (1) the intuitiveness of perception, comprehension and projection as necessary to operate complex systems and (2) the explicit connection to the widely adopted information processing model (Wickens et al. 2012). Another major factor underlying common adoption is that Endsley (1988a, 1995a) complements the three-level characterisation with a measure – situation awareness global assessment technique (SAGAT). The measure is an instrument for researchers and practitioners to advance or apply an apparently intuitive human performance notion that might have otherwise been a point of theoretical discussion.

SAGAT is the dominant SA measure, enjoying a similar intuitive appeal to the three levels of SA. SAGAT is the first SA measure adopting the now familiar query-/probe-based

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technique, which elicits declarative knowledge by directly questioning participants/workers in real time or during pauses in scenario trials or work settings. This technique intuitively connects the SA measurements with the notion. That is, the answers to the questions about the situation constitute (at least part of) the operator SA. In addition, the query-/probe-based technique accounts for the coupling between situation and awareness. Both the queries/probes and administration methods can be customised to the characteristics of the situation and awareness being investigated to promote construct validity. The coupling between situation and awareness becomes particularly important in industrial settings where expertise is highly specific to the work domain. This contrasts with rating scales used for other constructs that rely on static sets of questions (e.g. NASA TLX for workload).

Limitations of the three-level characterisation and SAGAT in process control

Despite their intuitive appeal, applying the three-level characterisation and SAGAT in process control is not as simple and direct as their formulation would suggest. Because of their domain-general nature, the three levels of SA and SAGAT lack the descriptive and methodological details associated with the unique coupling between the situation and awareness exhibited by process operators. The literature increasingly indicates the significance of domain specificity in SA. Durso and Drews (2010) illustrate that safety solutions in aviation are *not* directly transferable to health care because 'differences, especially at the micro level, impose limits on the analogy' (71). Bryant et al. (2004) present the Critique, Explore, Compare, and Adapt (CECA) descriptive model of SA for military command and control. They argue that CECA emphasises critical characteristics inherent in command and control but neglected by the three levels of SA. Lau, Jamieson, and Skraaning (2012, 2013) show how situation assessment in process control resembles problem-solving as opposed to information processing. Lau et al. also suggest that SA accounts describe operator cognition for their originating domains better than other ones, such as the three levels of SA for aviation.

Similarly, SAGAT lacks detailed, methodological prescriptions for developing and administering queries or probes that account for the coupling between situation and awareness in process control. For instance, SAGAT does not prioritise different process information. Nor does it guide the form of the queries/probes or responses so that they are compatible with the operations of process plants (cf. Cooper, Porter, and Peach 2014).

This lack of detailed methodological prescriptions of SAGAT for individual domains is evident in the diversity of query-/probe-based SA measures. Since the introduction of SAGAT, query-/probe-based measures have expanded to include Situation Awareness Control Room Inventory (SACRI; Hogg et al. 1995) for process control; Situation Present Assessment Method (SPAM; Durso and Dattel 2004; Durso et al. 1998), Situation Awareness bei Lotsen der Streckenflugkontrolle im kontext von Automatisierung[1] (SALSA; Hauß and Eyferth 2001, 2003) and Situation Awareness for Solutions for Human-Automation (SASHA) Partnerships in European air traffic management (Jeannot, Kelly, and Thompson 2003) for air traffic control; Quantitative Analysis of Situation Awareness (QUASA; McGuinness 2004) for command and control; and Analog SAGAT (ASAGAT; Gatsoulis, Gurvinder, and Dehghani-Sanij 2010) for tele-robotic control. These measures typically distinguish themselves by prescribing methodological details that account for properties specific to work situations and thereby improve the coupling between the situation and awareness in the measurements.

Publications on query-/probe-based measures focusing on the coupling between situations and cognitive work of process systems are sparse. SACRI, the only query-based measure for process control, integrates Endsley's three levels of SA and selected findings about process operators from the literature. SACRI is the predominant query-/probe-based measure in use for process control studies (Hallbert 1997; Lang et al. 2002; Sebok 2000), as domain-general, query-/probe-based measures cannot provide the methodological prescriptions specific to the work context of process control. However, research on the SACRI method has not continued beyond its initial development. SACRI could develop further to exploit the full range of available research on human operators in process control (see below). SACRI could also extend its empirical foundation beyond the initial pilot simulator studies recruiting mostly non-professional operators.

In summary, domain-general SA accounts and measures are useful for directing research attention towards an important class of measures. However, they fall short of providing descriptive and methodological details for individual domains. To support application of the notion in process control, SA characterisations must explicitly attend to properties of process plants and corresponding operator cognitive behaviours that are often neglected in domain-general accounts. Further, query-/probe-based SA measures must specify sufficient methodological details to ensure the compatibility with operator cognitive behaviours in managing process plants.

Merits of domain-specific characterisations of SA

Process control can benefit from domain-specific SA characterisations and measures. Domain-specific SA characterisations can capture the interaction between plant properties and process operator work demands, providing a basis for developing measures that tightly couple situation and awareness. Further, the detailed interactions captured by the characterisations can facilitate empirical testing and refinement that are more difficult to perform on abstract SA accounts. Finally, the characterisations can facilitate comparisons to other domain-specific accounts to identify generalisable SA characteristics and empirical findings (Lau et al. 2011).

Domain-specific SA measures can prescribe methodological details that simplify the work of the experimenters. This includes specifying the query/probe characteristics and administration methods that standardise the use of the measures. Standardising usage ensures consistency in measurement properties (i.e. sensitivity, reliability and validity) and interpretation of results across studies. Finally, well-specified measurement methods permit empirical testing and refinement that are difficult for measures that require substantial customisation for every use (e.g. SAGAT).

We have adopted a domain-specific perspective to investigate SA in process control for improving measurements in the domain. This approach leads to SA sub-dimensions conceptualised according to *process operator situation assessment activities* that bring about monitoring-, reasoning/diagnosis-, self regulating- and control-derived SA (Lau and Skraaning 2015; Lau, Skraaning, and Jamieson 2015). These SA sub-dimensions contrast dimensions conceptualised according to psychological models and processes (cf. perception, comprehension and projection by Endsley 1995b).

The set of situation assessment activities first investigated in depth is monitoring of process plants. *Process Overview* is formulated to characterise the knowledge or the *SA acquired through monitoring process plants (i.e. monitoring-derived SA)*. Process Overview thus represents one of several SA sub-dimensions in process control. Based on this domain-specific SA sub-dimension, *the Process Overview Measure* is developed *to assess SA derived from monitoring*.

This article presents the characterisation and measure of Process Overview. A companion article presents the empirical evaluation of the measure in full-scope simulator experiments. The remainder of this article is organised as follows. The section below summarises the literature on monitoring process plants and describes Process Overview. The next describes the Process Overview Measure based on the SA characterisation. A penultimate section compares the Process Overview Measure to SACRI and SAGAT on domain specificity and operationalisation precision. The final section discusses the merits of this work and the domain-specific approach to SA research.

Process Overview – SA from monitoring process plants

Process Overview is formulated according to field studies and observations reported in the process control literature. The first half of this section summarises process plant properties and operator monitoring behaviours. The latter half presents the formulation of Process Overview and draws implication for its measurement (Lau et al. 2011).

Properties and work demands of process plants

The properties of process plants exact work demands on operators, shaping their monitoring behaviours and defining the SA needed to operate the plants. Process operators cope with large numbers of tightly coupled components and automation in facilities that convert raw materials, often in large quantity. They manage mostly closed[2] (but large scale), causal systems with plant processes that are mainly represented by abstract scientific principles or concepts analogical to the physical phenomena. The operators must account for the slow, noisy and continuous nature of process dynamics. They must also adapt to operate the plants in events or circumstances that are unexpected by the designers due to plant complexity and long lifespan (see Lau, Jamieson, and Skraaning 2012 for details).

The demands of coping with large scale, pervasively automated, tightly coupled, slow responding, noisy, causal engineering processes with a long lifespan shape the monitoring behaviours of process operators. SA characterisation for process control should reflect these monitoring demands and behaviours.

Monitoring process plants and characterising SA

Monitoring is comprised of a diverse set of activities performed by operators to acquire information about the operating states and initiate further cognitive processes and control actions (e.g. Cara and Lagrange 1999; Edwards and Lees 1974; Mumaw et al. 2000; Rasmussen, Duncan, and Leplat 1987; Sheridan and Johannsen 1976; Wickens and Hollands 2000). Operators typically begin their shifts by conducting a shift turnover – a briefing on plant operating conditions between operators coming on duty and those being relieved. The turnover communicates the plant status, activities completed, activities outstanding and other special circumstances. Operators also review logs – chronological records of significant events and activities (e.g. tests completed, component failures) – to gain knowledge of recent plant status. Operators conduct panel walkthroughs surveying process parameters to gain a 'process feeling' in addition to observing specific process parameters and alarm displays at their workstations. Operators often communicate with field operators[3] and occasionally conduct field tours to collect information about the operating states outside the control room. Operators also participate in maintenance and testing work that requires proactive information gathering and processing. The diverse set of activities highlights three cognitive characteristics of monitoring that enable operators to cope with the properties of process plants: context building, top-down information sampling and semantic processing. In process control, monitoring is dominated by *active search* for information, as opposed to *passive discovery* of deviations.

Context and precision of knowledge content

Operators perform a myriad of activities to develop and maintain an *operating context* that facilitates selective observation of process parameters and alarms. This context can be a product of any of the following characteristics of process plants:

- Process plants often operate through component failures;
- Instrument readings considered appropriate in one setting can be dangerous in another;
- Equipment failures lead to unanticipated or even unintended operations (cf. Perrow 1995);
- Operational practices evolve over time in response to design deficiencies and external pressure; and
- Testing and maintenance occur in parallel with operations.

Given these plant properties and operations, process displays rarely present all necessary information for a given operating circumstance (see, cognitive underspecification in Reason 1990). Consequently, operators build operational contexts as an adaptive behaviour to cope with the limitations of plant control rooms due to the lack of operational knowledge during the design stage.

SA derived from monitoring needs to reflect operational contexts that provide guidance on which process areas to attend to and what process behaviours to expect. Operating contexts are relatively ill-defined and imprecise, suggesting that monitoring involves a broad search of plant information to compare actual and expected states. Further, search strategies are often guided but not wholly normative. Thus, monitoring-derived SA from monitoring is an *overview* of the plant state that is difficult to fully specify.

Top-down sampling and relevance of knowledge content

Operators frequently employ a *top-down sampling* of process and automation indicators based on the operating contexts (Edwards and Lees 1974; Mumaw et al. 2000) and their representation of the process plant (see Moray 2006). Based on their extensive field observation at a nuclear power plant, Vicente, Mumaw, and Roth (2004) developed a monitoring model capturing that operators employ their knowledge and experience to direct their attention towards the subset of parameters relevant for the situation. Vicente et al. further argue that 'the operator needs to make a series of other decisions before actual monitoring activities can commence' (371) because the scale of process plants prohibits continuous, comprehensive and reliable sampling of all process parameters (Moray 2006). In addition to scale, operators must account for the effects of automation, such as identifying masking (Duncan 1987). Tight coupling between components also necessitates interpreting any process parameter in relation to several others. Nevertheless, process operators can rely on tight coupling to sample a subset of process parameters that could be sufficiently indicative of process states. In essence, operators are always deciding what process areas should be prioritised for closer observation and how one observation made in relation to the operating contexts could inform subsequent monitoring behaviours. The work of naturalistic decision-making and macrocognition (e.g. Schraagen et al. 2008) synthesises the findings on top-down approach to system monitoring in multiple domains.

SA derived from monitoring needs to reflect top-down sampling of process indicators to manage plant complexity with limited cognitive resources. A corollary to the top-down monitoring approach is that monitoring-derived SA contains neither complete nor random process information. Further, awareness about which parameters and automation components require attention appears to be more important than awareness of absolute parameter values and automation activities. Monitoring concerns active information search (also see, Rouse 1979a, 1979b). Thus, monitoring-derived SA is an overview of the plant state that *highlights the subset of process behaviours requiring operator intervention*.

Semantic processing and significance of knowledge content

Operators engage in *semantic processing* to account for the complex behaviours of plant processes, instrumentation and automation that preclude normative indicator values or control actions satisfying all circumstances. For instance, operators do not treat alarms as absolutely true or false according to signal detection theory because, in some contexts, certain alarms are indicators of ongoing activities, such as maintenance work, rather than hazards (Guerlain and Bullemer 1996; Lees and Lee 2007; Xiao and Seagull 1999). The merit of alarms that are intended to identify 'known' hazards has been shown to be a function of the situation and operator expertise (Bitan and Meyer 2007; Meyer and Bitan 2002). That is, monitoring alarms requires considerable operator judgment. Another example is that process operators often monitor according to 'action time' as opposed to 'clock time' (de Keyser 1987)[4]; probably because transitions between plant states can differ from one instance to another in terms of time progression and parameter changes. Further, many processes respond slowly to control actions and some parameters change in complex ways (e.g. stepwise function), obscuring the true states or behaviours of processes.

The lack of normative values for comparison also suggests that distinguishing between normal and abnormal parameter changes is difficult. In addition, expecting operators to predict individual process parameter values can be unrealistic. Parameter behaviours are products of both initial process faults and operator control actions, some of which are undertaken to provide observation for hypothesis testing. Parameter predictions are inseparable from decisions and consequences of operator actions (see, Lau, Skraaning, and

Jamieson 2009), challenging the study of operator prediction in an objective and reliable manner (Wickens 2015). Hence, monitoring is not a vigilance task of checking process values against limits that would lead to direct conclusions about plant states (also see, Moray and Haudegond 1998).

SA derived from monitoring needs to reflect the semantic processing of process dynamics. The complexity of process dynamics severely limits the utility of 'normative' values and predictions of process parameters. This shapes operator SA in two ways. First, process dynamics encourage operators to translate parameter changes from scientific units (e.g. clock time) to magnitudes of operational significance (e.g. action time). Second, due to limited precision in mental processing of plant dynamics, anticipation generally occurs at a 'macro' level (i.e. plant states or general parameter behaviours) and is expressed in the form of attention to critically changing parameters as opposed to mental projections of parameter values (e.g. Cara and Lagrange 1999). Thus, monitoring-derived SA is an overview of the plant state that reveals a subset of *process behaviours deemed significant for the operating conditions*.

SA characterisation – Process Overview

Process Overview is formulated to depict knowledge/awareness derived from monitoring. This knowledge needs to reflect the array of monitoring activities – building and updating context, observing process parameters, recognising relevance of sub-processes, deciphering significance of the process behaviours and ultimately perceiving the true process deviations. Process Overview is therefore a Gestalt view of plant processes with anomalies in the foreground isolated from the normal processes in the background. Process Overview represents an imprecise view of the plant conditions highlighting a subset of significant and relevant process behaviours.

Measurement application of Process Overview

Process Overview informs measurement of operator SA by specifying the characteristics of the knowledge that is practically necessary to monitor process plants given the available resources, thereby prescribing the type of knowledge that is important for measurement in realistic process control settings. Measures of Process Overview should therefore reflect (at least) three characteristics: (i) the highly contextualised nature of monitoring process plants, (ii) the top-down sampling of plant indicators and (iii) the semantic processing of significance of indicator values.

First, Process Overview is context-dependent; therefore, any form of data collection and assessment should be performed as close to the context or scenario as possible. In other words, situating the measurement in the operational context could improve representativeness.

Second, Process Overview is built from a top-down sampling of indicators. Thus, relevance of the sampled indicators to the context and disturbances is a critical indication of monitoring. Thus, measures should seek knowledge and sample process parameters pertinent to the scenarios rather than random information or any parameter readings about the process.

Third, Process Overview reflects semantic processing necessary to account for the process dynamics and operational significance. Measures should aim to include operator judgment on operational significance of parameter changes and timing rather than recall or prediction of precise changes.

Increasing domain specificity in SA measures

The Process Overview Measure

The Process Overview Measure operationalises Process Overview as the accurate detection of meaningful changes in relevant process parameters. The parameters are *relevant* when they effectively represent the operating contexts or reveal potential anomalies. Parameter changes are *meaningful* when they represent the systematic trends as opposed to (uninformative) fluctuations.

During the preparation phase of a simulator experiment or evaluation session employing the Process Overview Measure, process experts are asked to perform three interconnected tasks: (i) develop or review scenarios, (ii) select relevant parameters and (iii) identify simulator-freeze points for query administration.

First, process experts are usually responsible for developing scenarios with characteristics that are relevant to the purpose of the study (see Skraaning 2003). For instance, to evaluate an alarm system, the scenarios must contain process events or faults leading to alarms. The Process Overview Measure does not prescribe any guidance for developing scenarios. Rather, the measure relies on process experts to develop representative scenarios that are useful for studying the experimental topics, sufficiently challenging to operators and satisfying various practical constraints (e.g. availability of operators).

Second, process experts select *relevant* process parameters that represent the operating context and process events (including faults) in the scenario. In other words, the operators/participants successfully monitoring the process during the scenarios are expected to know the behaviours of these parameters. This awareness is elicited through administration of queries of the form specified in Figure 1.

Relevant parameters can typically be classified as (i) context-sensitive or (ii) fault-sensitive (Lau et al. 2011). *Context-sensitive* parameters reflect the overall plant states based on the operating contexts described to the operators at the beginning of the scenarios. For instance, during start-up

Process Overview Query Structure:
Recently, the parameter [code] has:

Process Overview Response Alternatives:
Increased/Stayed the same/Decreased

Figure 1. The Process Overview Measure: the query and response format (Also presented in Lau et al. 2011).

at a certain power level, operators often sample a set of key parameters periodically. The cuing effects for context-sensitive parameters should be negligible as these parameters are emphasised during training and work practice.

Fault-sensitive parameters reveal the process faults introduced by the scenarios and therefore require close observation. Operators may not sample these fault-sensitive parameters during normal operations. Thus, fault-sensitive queries may be subject to cuing effects, prompting consideration of the method by which these parameters are introduced.

Third, process experts select the timing for the simulator freezes to administer queries in each scenario. The number of freezes per scenario should be based on the amount of data required to achieve statistical power for the study. The selected process parameters and scenario characteristics govern the timing of those freezes. Context-sensitive queries relevant for the entire scenarios may be administered at random times. Other context-sensitive parameters become relevant or irrelevant as the scenarios progress, so their administration needs to be selective.

The timing of fault-sensitive queries needs to coincide with the introduction of the faults without resulting in cuing effects that would impact analysis and results. Two general methods are available to counteract cuing effects of administering fault-sensitive queries. The first method relies on strategically timing alarms to occur immediately after the freeze so that all operators are directed towards monitoring the same parameters. In effect, all the operators would have similar knowledge of the process fault after the freeze, levelling the playing field irrespective of cues provided by the queries. Take the case in which a valve malfunctions leading to a slow increase in water level of a heat exchanger and eventually a high level alarm. Immediately before this high level alarm, a freeze can occur to administer fault-sensitive queries about the valve and heat exchanger level. The second method relies on administering the queries at the end of the scenarios when the cues from the queries cannot influence operator performance.

The three process expert tasks – scenario development/review, parameter selection and freeze timing – are interconnected and often iterative. For instance, the scenarios may be redesigned to provide effective strategic timing of freezes to administer fault-sensitive parameter queries immediately before an alarm. Process experts should consider the use of scenario characteristics, parameter selection and freeze timing in relation to each other to optimise the quality of the SA measurements with respect to the purpose of the empirical studies.

In the course of a scenario trial, the simulator should freeze at the times specified by the process experts. During freezes, the participants answer the corresponding set of queries without any access to process displays. The participants' answers are labelled as *responses*. At the same time, the process experts supporting the data collection answer the queries with access to all the process displays. The process expert answers are labelled as *reference keys*. In addition to collecting the responses and reference keys, the simulator logs the parameters throughout the scenario for potential verification needs after the experiment.

After the data collection, final scores are calculated as the proportion correct (or matches) between the responses and reference keys.

Comparison to SACRI and SAGAT

Comparing the Process Overview Measure to SACRI and SAGAT serves to highlight the methodological prescriptions of the former that reflect the unique interactions between the operational nature of process plans and cognitive behaviours of process operators (Lau et al. 2011).

SACRI

SACRI (Hogg et al. 1995) is a query-based SA measure intended specifically for process control and is the precursor to the Process Overview Measure. Adopting the three-level characterisation of SA for its theoretical basis, SACRI prescribes the creation of an inventory of parameters that can represent all plant states or processes based on a review of plant documentation and discussion with the plant operators. SACRI structures queries to elicit operator knowledge about past, present and future changes in these parameters (see Figure 2). SACRI also provides four optional sets of responses for the queries but does not provide any guidance on selecting between them (Figure 2). The simulator freezes in SACRI are predetermined by the experimenters based on their research interests. During the data collection phase, the participants operate a high-fidelity simulator and answer queries randomly drawn from the inventory at the pre-determined times of simulator freezes. Operators respond to the queries without access to the simulator displays. Upon completion of the queries, operators continue with the scenario trials. During the data analysis phase, the reference keys

Past, Present and Future SACRI Queries:

(i) In comparison with the recent past, how has the parameter [code] changed?
(ii) In comparison with normal status, how would you describe the parameter [code]?
(iii) In comparison with now, predict how the parameter [code] will develop over the next few minutes.

Response Sets for SACRI Queries:

(i) Increase/Same
(ii) Decrease/Same
(iii) Increase/Same/Decrease
(iv) Increase in more than one/Increase in one/Same/Decrease in one/Decrease in more than one/Drift in both directions

Figure 2. SACRI – query and response format. Based on Hogg et al. (1995) and also presented in Lau et al. (2011).

for the queries are determined by reviewing simulator logs[5]. Operator responses to the queries are then characterised in terms of signal detection theory (SDT; McNicol 2005).

SAGAT

SAGAT (Endsley 1988b, 1995a, 2000) is a domain-general measure for collecting data in medium- to high-fidelity simulator experiments. SAGAT prescribes conducting a goal-directed task analysis to help identify query content that operators should perceive, comprehend and project in order to fulfil their job requirements. SAGAT does not prescribe any specific format for structuring queries or responses, although the typical format is multiple choice. SAGAT prescribes random timing and selection for administering the queries across scenarios to reduce cuing effects. Each pause should be between five and ten minutes in length. For the data collection phase, participants operate a simulator in multiple scenarios and respond to the queries during pauses of the experimental trials without access to the simulator. SAGAT does not prescribe any specific scoring methods but proportion correct is most common.

Comparison in operationalisation

The Process Overview Measure is the result of ongoing efforts to increase the precision of operationalisation for query-based SA measurement techniques in realistic process control environments. Table 1 illustrates the progression of operationalisation precision through domain specificity across SAGAT, SACRI and the Process Overview Measure.

Theoretical basis. The theoretical basis for the Process Overview Measure is the knowledge derived from monitoring process plants (Lau, Jamieson, and Skraaning 2012), focusing on work activities in the domain as opposed to psychological activities in general. This contrasts with SACRI and SAGAT, both of which adopt the three levels of SA built on the information processing model. SACRI does incorporate field research in process control (e.g. Roth, Mumaw, and Stubler 1992, also see, Hogg et al. 1995) to put Endsley's three levels of SA in context. However, we argue that shifting the theoretical emphasis from psychological activities towards work activities increases the specificity of methodological prescriptions, thereby improving operationalisation precision for measuring SA in the process control domain.

Query content characteristics. The differing theoretical bases lead to different methodological prescriptions and therefore specificity across the three measures. The Process Overview Measure and SACRI have similar prescription for the content and form of the queries and responses because field research suggests that process operators tend to think in terms of parameter behaviours. As presented in Figures 1 and 2, the Process Overview Measure and SACRI restrict content variations of queries to plant parameters and prescribe specific forms for both queries and responses. In contrast, SAGAT provides only lexical definitions of perception, comprehension and projection. Guidance based on lexical definitions can lead to substantial variation between individual uses of SAGAT. In brief, both Process Overview and SACRI offer more precise methodological prescriptions than SAGAT, but limit their applications to the process control domain.

Query temporal characteristics. The Process Overview Measure further restricts queries about parameter behaviours to the recent past. This contrasts with SACRI, which elicits knowledge about parameter behaviours in the past, present and future. The Process Overview Measure excludes queries about the present because such queries are difficult to interpret. In SACRI, parameter behaviours about the present can be classified as *normal* or *abnormal*[6] but correct response would depend on the interpretation of 'normal status' with respect to the process faults. If operators

Table 1. Similarities and differences between SAGAT, SACRI and the Process Overview Measure.

	SAGAT	SACRI	Process Overview Measure
Construct/Theory	Model/3 Levels of SA by Endsley (Endsley 1995b)	Model/3 Levels of SA by Endsley (Endsley 1995b) augmented with research on process plant monitoring	Process Overview as a SA sub-dimension derived from monitoring process plants (Lau, Jamieson, and Skraaning 2012)
Elicitation method	Queries during simulator freezes in each trial		
Query characteristics	Level 1, 2, 3 SA as classified according to the researchers (i.e. perception, comprehension & projection)	Behaviours of process parameters in the past, present and future	Behaviours of process parameters from last meaningful change to the present
Query development	Goal-directed task analysis	System documentation and discussion with process experts to build an inventory for a specific power plant	Scenario analysis by process experts
Query selection	Random selection based on job classes	Random selection (with constraints) from inventory	Strategic selection according to scenario characteristics
Timing of query administration (i.e. freezes)	Random timing	Strategic timing based on scenario characteristics	
Response format	No requirement but typically with categorical choices (i.e. multiple choice)	Select one of the four prescribed sets of Alternative-forced-choice	3-Alternative-forced-choice (increased, stayed the same, decreased)
Reference key to the queries	Post-trial assessment based on simulator data logs and judgement of subject-matter experts	Post-trial assessment based on simulator data logs	Real time assessment by process experts
Scoring	Percentage correct (typical)	Non-parametric formula for calculating Sensitivity and Bias in signal detection theory	Percentage correct

take process faults into consideration, the undesirable parameter behaviours are 'normal' given the abnormal circumstances. Of course, the parameter behaviours are not 'normal' relative to the desired operating situation. However, there appears to be no practical means within the scope of query-/probe-based technique to elicit or determine how the operators respond to each query.

Future/prediction queries are deemed inconsistent with cognitive work of process operators, and difficult to assess independent of operator decisions and control actions. First, operators anticipate process parameters that need close observation but rarely can predict their specific behaviours, especially in complex operating conditions (e.g. Cara and Lagrange 1999). Second, projected parameter values can be difficult to verify because future values are consequences of operator decisions and actions as well as the process faults (also see, Wickens 2015).

Response sets. The Process Overview Measure restricts response options for all queries to a single set – increased, decreased and stayed the same – that forms a theoretically complete set of parameter behaviours. This contrasts with SAGAT, which does not predefine any response options or format. SAGAT does recommend multiple choice but there is no guidance for appropriate options/distractors. Although this flexibility allows SAGAT to be domain-general, it leaves methodological details to be developed by experimenters. SACRI predefines four optional sets of responses, one of which is identical to the Process Overview measure. SACRI does not provide any guidance for choosing between the sets.

Content selection. The Process Overview Measure identifies the contents for individual queries differently from both SACRI and SAGAT. The Process Overview Measure and SACRI rely on process experts to identify the parameters that should be inserted into the predefined queries. For the Process Overview Measure, process experts determine a set of parameters that are both content- and timing-relevant for the scenarios. The Process Overview Measure relies on incorporating scenario characteristics (e.g. alarms) to mitigate cuing. These two methodological prescriptions are driven by the fact that process operators can only attend to what is practically necessary in the scenario as opposed to the thousands of indicators in a process plant. On the other hand, under SACRI, process experts determine an 'inventory' of parameters relevant to all plant operations, whereas SAGAT prescribes conducting a GDTA to identify contents for queries at the three SA levels for all operations.

Query administration timing. SACRI and SAGAT prescribe random selection of queries for administration during the experimental trials. This adherence to psychological convention emphasises experimental control (i.e. limitation of cuing effects). In contrast, the query contents and administration timing for the Process Overview Measure focus on the coupling between situation and awareness.

Reference keys. The Process Overview Measure prescribes that process experts determine the reference answers during the freeze based on (1) full knowledge of the scenarios, (2) observation of participants operating the plant or simulator and (3) access to process displays. During the scenario trials, contextual information about the scenario, operator control actions, process behaviours and related parameter values are available to the process experts to assess changes in process parameters. In contrast, SAGAT[7] and SACRI recommend *post hoc* assessment of parameter changes based on graphs from simulator logs[8]. Such a detached setting could make it significantly more difficult to incorporate relevant operational information.

Scoring. The Process Overview Measure uses proportion correct as the performance index of Process Overview. SAGAT also typically uses proportion correct. In contrast, SACRI employs sensitivity and response bias, which are useful indices of performance, but the three alternative-force-choice response sets prescribed by SACRI does not conform to SDT. (For SA measures with bias scores, see Rousseau et al. 2010, McGuinness 2004.)

Discussion

This research adopts a domain-specific approach to capture unique interactions between process plant properties and operator cognitive behaviours that are neglected by domain-general SA accounts and measures. Process Overview is developed to characterise a sub-dimension of SA by synthesising the literature on monitoring process plants. This characterisation is applied to guide the design and administration of queries for maximising the coupling between situation and awareness in the Process Overview Measure.

The Process Overview Measure, SACRI and SAGAT are compared to highlight the methodological differences resulting from adopting the domain-specific approach. The comparison illustrates that SAGAT represents a measurement framework adopting Endsley's model of SA rather than an actual measure or operationalisation of SA. That is, SAGAT provides general directions based on lexical definitions of the three SA levels, goal-directed tasks analysis and classical psychological experimental controls for collecting the query/probe-based human performance data. This approach leaves the flexibility for researchers and practitioners to customise queries and administration methods for many different tasks and domains. Consequently, SAGAT lacks prescriptions for the selection of the content and form for the queries and response formats that could affect measurement properties of the SA scores. In essence, the main contribution of SAGAT is directing attention to the query-/probe-based technique that can be carefully adapted for applications in specific domains.

The Process Overview Measure and SACRI specify methodological details in the content, phrasing and response formats of the queries based on field and observation studies in process control. For instance, the main variation between queries for both measures is the selection of specific process parameters. The improved methodological details over SAGAT can reduce variation across studies, providing assurance for generalising measurement properties and lowering workload for the experimenters. However, the application of research findings specific to process control inherently precludes the use of the Process Overview Measure and SACRI in other domains. In brief, the Process Overview Measure and SACRI provide detailed instruction and standardisation in collecting query-based measurements.

Besides standardisation and simplification for applications, the methodological prescriptions of Process Overview Measure and SACRI are intended to improve the coupling between the situation and awareness in the query-based measurements. For instance, the Process Overview and SACRI queries elicit parameter behaviours rather than exact values, matching how process operators monitor process plants (e.g. Roth, Mumaw, and Stubler 1992). This approach resonates with the SALSA method of administering queries according to a event-based model, which is based on how air traffic controllers monitor airspace (Hauss and Eyferth 2003). Both the Process Overview Measure and SACRI prescribe strategic rather than random timing of freezes in scenario trials to focus on scenario-relevant knowledge for each administration of queries.

Differences in the methodological prescriptions of the Process Overview Measure and SACRI can be traced to the degree of commitment to the domain-specific approach. For instance, in adopting the three levels of SA characterisation, SACRI prescribes queries that elicit knowledge about future parameter behaviours, which the Process Overview Measure omits. Further, SACRI also prescribes random selection of process parameters for the queries, which is inconsistent with top-down sampling characterised in Process Overview. These methodological differences illustrate that adapting domain-general SA measures does not necessarily yield the results of developing domain-specific ones.

The unique methodological details in the Process Overview Measure indicate that domain-specific SA characterisations can capture important interactions between domain properties and cognitive behaviours that are neglected in domain-general accounts. The details captured and reflected by the Process Overview characterisation and measure can be subjected to empirical testing more readily than domain-general accounts and measures. For instance, the response options specified in SACRI and the Process Overview Measure can be tested empirically to inform both SA measure and theory development. In contrast, domain-general SA accounts and measures typically do not contain such readily testable methodological details.

Domain relevant details and readily actionable/testable methods are important to the operational communities that 'can be incredibly suspicious of academics theorizing' (Byrne 2015, 85). This suspicion is not surprising as new theoretical debates have arisen while old ones have continued over two decades of SA research and application; as reflected in three journal special issues on SA from Human Factors in 1995, to Theoretical Issues of Ergonomics Science in 2000, and then Cognitive Engineering and Decision Making in 2015. Endsley remains resolved on her *still* incumbent SA theory (cf. Endsley

2015b, 2015a, 2004, 1995b) when contested by legacy challenges (cf. Flach 1995; Hoffman 2015) and new theories (e.g. Chiappe, Strybel, and Vu 2015; Stanton, Salmon, and Walker 2015). Until domain-general theoretical debates are resolved, domain-specific SA research, as exemplified by the Process Overview characterisation and measure, may offer the readily testable ideas or methods being sought by individual operational communities.

In pursuing operational precision, both the Process Overview characterisation and measure sacrifice not only domain generalisability but also coverage of the SA notion. The Process Overview characterisation and measure covers only one sub-dimension of SA in process control, thereby imposing a limit of content validity in SA assessment. From this perspective, SACRI and SAGAT arguably have greater content validity than the Process Overview Measure. However, the logic of such an argument assumes that other sub-dimensions are 'well' formulated and that the query-/probe-based technique is appropriate for measuring all SA sub-dimensions in process control. However, this assumption needs to be tested theoretically, analytically and empirically. Our research suggests that other SA sub-dimensions in process control need further investigation and that the query-/probe-based technique does not appear appropriate for measuring them all (Lau and Skraaning 2015). For example, the query-/probe-based technique may introduce too much cuing or mis-cuing to measure reasoning derived SA, which only captures the specific process faults and behaviours given the operating condition. Our current view is that the query-/probe-based technique is most appropriately applied to measuring monitoring-derived SA that reflects the effectiveness of information gathering by operators. Further research is necessary to achieve content-valid SA assessment.

Corollary issues

Empirical evaluation is necessary to assess whether the Process Overview Measure is able to collect sensitive, reliable and valid measurements. The companion article augments formulating the characterisation and measure of Process Overview with evaluating various measurement properties in high-fidelity simulator experiments. The article also summarises the findings in terms of theory, associated techniques, practical application experience, limitations as well as measurement properties (as proposed by Stanton 2014).

Future work

The Process Overview characterisation and measure only describe and measure SA derived from monitoring process plants, respectively. Reasoning and self-reflection are two other major categories of situation assessment activities (Lau, Jamieson, and Skraaning 2012) and knowledge characterisations for those activities are still needed to represent SA fully in process control. Applying domain-specific SA characterisations to develop measures will then improve content validity of SA assessment. Further, appropriate techniques to measure these other categorically different SA characterisations/dimensions deserve systematic examination.

Domain-specific characterisations and measures facilitate explicit comparison of SA characteristics across domains that can be invaluable for SA research and applications. While the literature contains many reviews and comparisons of SA accounts and measures (e.g. Salmon et al. 2008; Salmon et al. 2006), an analysis framework and technique that support systematic comparisons of SA characteristics across domains do not exist. Future work is necessary to develop such an analysis technique and perform the comparison of SA applications across domains.

Conclusion

Process Overview is a domain-specific SA characterisation depicting operator knowledge acquired through monitoring a process plant. Its formulation is built on field research and observation specific to process control work activities as opposed to psychological processes or cognitive abstraction of work.

The Process Overview Measure is a query-based SA measure that operationalises Process Overview. Its methodological prescription is driven by work activities to maximise the coupling between situation and awareness in the measurements. In prescribing methodological details that account for process control domain properties, the Process Overview Measure should improve measurement sensitivity, validity and reliability in this domain. These prescriptions should also standardise the measurements across studies and simplify the work of experimenters associated with customising and administering the queries.

Comparing SAGAT, SACRI and Process Overview Measure indicates that adapting domain-general SA measures does not necessarily produce domain-specific measures, highlighting a need to study SA systematically at the domain level. In the companion article, two full-scope simulator studies are reported to start establishing the empirical basis on the measurement properties of the Process Overview Measure.

Notes

1. Translated 'SA of Area Controllers within the Context of Automation' from German.
2. Although process plants are mostly closed to external disturbances, they can be dramatically impacted by external events such as the tsunami that incapacitated the Fukushima nuclear facility.
3. Field operators are usually responsible for managing specific equipment in the plant. For instance, control

room operators often ask field operators to check the operations of a valve. Field operators also inform control room operators if they witness equipment malfunction in the plant.

4. We can relate to this experience in our daily activities. For instance, time perception for a conversation is content-based rather than clock-based. Consequently, people can generally recall a portion of conversation more accurately by referring some content rather than time markers. (e.g. What did we talk about after discussing the dinner menu? What did we talk about fifteen minutes ago?).
5. The general criteria are that the changes should be (i) observable on displays, (ii) detectable on plots of appropriate scale, (iii) large compared to the baseline established by normal simulator runs, (iv) illustrative of predominant parameter trends and (v) enclosed in an approximately three-minute interval (for past and future queries).
6. The alternatives of increasing, stayed the same and decreasing are not applicable to describing parameter behaviour in the present because a parameter change must be described with respect to a time period.
7. Note that SAGAT does employ process experts to determine reference answers to queries that cannot be obtained from the simulators including Level 2 – Comprehension questions (Endsley, 2000).
8. Specifically to SAGAT and SACRI that include prediction queries, reference keys for prediction queries may be collected by running scenario trials without operator intervention. This method has two caveats. First, the method is only applicable at the end of the scenario when operators no longer affect parameter changes. Second, the method may still require experts to account for process dynamics (e.g. a very slow increase in reactor power).

Disclosure statement

No potential conflict of interest was reported by the authors.

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