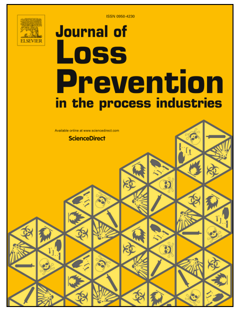
Accepted Manuscript



How to recognise a kick: A cognitive task analysis of drillers' situation awareness during well operations

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PII: S0950-4230(16)30178-4

DOI: 10.1016/j.jlp.2016.07.003

Reference: JLPP 3259

To appear in: *Journal of Loss Prevention in the Process Industries*

Received Date: 14 March 2016

Revised Date: 30 June 2016

Accepted Date: 1 July 2016

How to recognise a kick: A cognitive task analysis of drillers' situation awareness during well operations.

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Keywords: Kick Detection; Situation Awareness; Cognitive Task Analysis; Drilling; Safety.

Abstract

Purpose: The ability to monitor and detect anomalous changes in an oil well is a fundamental aspect of an offshore driller's job, so as to maintain well control, the safety of the surrounding rig and minimize risk. Drillers are required to have a high level of situation awareness in order to recognize and interpret indicators that suggest that hazardous hydrocarbons may have entered the well bore (referred to as kick detection), allowing them to take the best actions to deal with the situation. The aim was to use cognitive task analysis methods to identify the expert SA skills required for the complex task of kick detection.

Method: An Applied Cognitive Task Analysis (ACTA) of the SA components required for kick detection was conducted. 1. A technical task description was produced, using material extracted from well control manuals and a five day training course. 2. The SA components required for the kick detection task using the preliminary Drillers' SA model. 3. The ACTA data were validated by three drilling experts.

Results: The specific cognitive skills associated with maintaining SA that were required for accurate kick detection were: attending to and recognizing changes in the drilling parameters, understanding their significance as kick indicators in the context of a mental picture of the well state, and anticipating what could result in a kick, necessitating flow checking and/or shutting in actions.

Limitations: ACTA methods are prone to research bias however actions were taken to minimize this.

Practical Implications: Training and work design recommendations based on the ACTA are outlined for supporting driller SA for effective well control and consequently to improve process safety. The study also illustrates how ACTA methods can be used to examine and support cognition in the workplace.

1. Introduction

A fundamental aspect of an offshore oilfield driller's job is the ability to monitor and detect changes in the well state, which could indicate that control of the hazardous hydrocarbons has been compromised, so as to take the best actions to mitigate any adverse consequences. Should well control be lost (i.e. the downward hydrostatic pressure of the column of drilling fluid is exceeded by the upward formation pressure), an uncontrolled influx of fluids into the wellbore can occur with the potential to escalate into a kick, such as happened on *Deepwater Horizon (*see Report to the President, 2011; Chemical Safety Board, 2016*)*. Consequently, kick detection (i.e. the task of detecting changes in well state that indicate a kick could occur) is a safety critical aspect of not only well control, but of the safety of the (approximate 120) crew on board the drilling rig. The ability to remain vigilant for changes in the well state, to recognise and understand the significance of kick indicators for the unfolding situation refers to Situation Awareness (SA). SA is the state of knowing what is going on during task execution and using that understanding to predict how situations may develop (Endsley, 1995). Research has indicated that drillers require high level SA, particularly during complex tasks such as well control (Roberts, Flin & Cleland, 2015a).

Given the importance of maintaining well control, drill crew are required to complete mandatory, certified well control courses with examination on both theoretical and practical components including kick detection (IOGP, 2012). However, despite the importance of SA and other cognitive skills for kick detection, well control courses tend to focus on the technical aspects (e.g. managed pressure drilling; Elmore, Medley & Goodwin, 2014). It is positive to note that IOGP (2014, a, b) have outlined guidelines for conducting a Crew Resource Management (CRM) training program for well operations which includes SA (e.g. SA skills, symptoms of SA problems and how to combat them) but these require further research.

Coupling the expansion of the drilling industry into increasingly hazardous high-pressure high-temperature and deep water wells, with a demographic shift of large numbers of experiencing drilling personnel retiring (Johnson, Leuchtenberg, Petrie & Cunningham, 2014), the importance of understanding the SA expertise required for kick detection becomes ever more important for maintaining safety. Cognitive task analysis methods have previously been used in other process industries (e.g. nuclear power plants; Carvalho, dos Santos, Gomes, Borges & Guerlain, 2008) to examine expertise so as to develop interventions that support the operator's cognition (e.g. interface design for nuclear power plant control rooms, Kim, Suh, Jang, Hong & Park, 2012) and consequently improve process safety.

This paper utilizes the Drillers' SA model (Roberts, Flin & Cleland, 2015a) as the basis for an applied cognitive task analysis to identify the key SA components required for the offshore drillers to complete the safety critical task of kick detection. It illustrates how cognitive task analysis methods can be used to inform interventions that support the operator, such as training, accident analysis, error management and design of the working environment and technology.

1.1. Kick detection

Faster recognition of kick indicators is vital for an effective response to reduce the risk of adverse consequences (Fraser, Lindley, Moore & Vander Staak, 2014). Should a kick be recognised, the driller is required to remotely close the blow out preventer equipment on the sea floor to prevent the highly pressurised hydrocarbons from travelling up to the rig and resulting in a blowout, referred to as *shutting in*. Similarly should a kick indicator be recognised, the driller is required to assess the integrity of the well by observing whether the flow from the well is stable, referred to as a *flow check*. Thus, the driller's ability to constantly monitor, recognise and comprehend indicators from the wellbore is vital for kick detection and should a well control situation occur, the best decisions and actions are taken.

1.2 Situation awareness

Situation Awareness (SA) is the awareness of what is happening in the work environment, understanding what the information means, and using it to anticipate how situations will develop (Endsley, 1995; 2015). The disastrous consequences that SA failures (e.g. missing indicators) can through poor decision making and unnecessary risk taking have been recognised in process safety (Kaber & Endsley, 1998; Taylor, Wijk, May & Carhart, 2015) (e.g. *Deepwater Horizon*; Roberts et al., 2015b; *Texas City*; Khan & Amyotte, 2007; explosion at the chemical production facility *West Virginia Institute*, Naderpour, Nazir & Lou, 2015). A range of SA theories has been proposed (e.g., Smith and Hancock, 1995; Stanton, Salmon, Walker & Jenkins, 2009; Wickens, 2002). Despite a continuing theoretical debate on SA (e.g. see Dekker, 2015; Endsley, 2015), Endsley's (1995) three level model of SA currently remains the mostly widely applied in a broad range of high risk domains (e.g. nuclear power plants, Lee, Park, Kim & Seong, 2012; drilling, Sneddon, Mearns & Flin, 2006). SA is described by Endsley as a cognitive product of three hierarchical levels, perception (Level 1), comprehension (Level 2) and prediction (Level 3), identifying task and environmental factors (e.g. interface design and complexity), as well as individual factors (e.g. goals and experience) that can influence it. SA is supported through operators' tacit mental models of the systems and environment that they work in, allowing them to develop mental pictures of the current situation, as based on their experience/expertise (e.g. see Endsley & Garland, 2000).

1.3 Situation awareness research for kick detection

There is a minimal body of research examining SA in drilling, identifying problems such as failures to monitor or observe data (Sneddon, Mearns & Flin, 2006), drillers' poor concentration, and difficulties with interpretation of information (Stanton & Wilson, 2001), as well as with poorly designed aspects of the work environment (Sawaryn, Pickering & Whitely, 2008;Woodcock & Toy, 2011). The self-report Work Situation Awareness rating tool was employed to examine the impact on stress, sleep disruption and fatigue on SA, as well as the relationship between SA and unsafe behaviour and incident involvement in drilling (Sneddon, Mearns & Flin, 2013). Interviews with drill crew members and observations of well control scenarios in a high-fidelity simulator were conducted and utilized to develop the Drillers' SA model (Roberts et al., 2015b) (see Figure 1), as based upon Endsley's (1995) three level model. It reflects a cyclic process of attending to and gathering information from the surrounding environment, recognizing patterns from available indicators; interpreting their significance and utilizing mental simulations of how the situation may develop so as to take preparatory actions.

Insert Figure 1 approximately here.

More recently, the Drillers' SA model has also been used to examine process safety in the drilling industry as an accident analysis framework to examine the drill crew's SA on Deepwater Horizon (Roberts et al., 2015b). It provided insight into the crew's likely cognitive processes in the lead up to the blowout and why the crew erroneously believed that the well was stable despite indicators to the contrary. Whilst these studies are valuable for examining drillers' cognition, they discuss the general cognitive skills associated with well control, rather than kick detection specifically.

1.4 Cognitive task analysis

Cognitive Task Analysis (CTA) methods can be used to identify the cognitive processes and goal structures that underpin how experts perform complex tasks (Militello & Hutton, 1998)., such as kick detection This commonly includes conducting a Task Analysis (TA) in which task data (e.g. document analysis) are gathered to document what an operator is required to do to successfully complete a specified task within a system, producing a task description, (e.g. steps and actions; Stanton, 2005). Hierarchical Task Analysis (HTA) is a popular form of TA as it provides a straightforward method of breaking down a task into increasingly smaller nested tasks to investigate the minute details of task actions, goals and associated decisions (Stanton, 2005). The method is valuable as the task description and output of HTA's can be used for other activities such as conducting CTA, risk assessment, human error identification and Systematic Human Error Reduction and Prediction Approach (SHERPA; Stanton, 2004). CTA is an extension of traditional TA methods, examining cognitive expertise, using techniques including interviews, observations and questionnaires, such as were used to develop the Drillers' SA model. Roberts et al. (2015a) previously used CTA methods to examine drillers' SA; however, their study identified the generic SA skills used while drilling rather than explicitly outlining the precise SA steps for the particular task of kick detection. Similar to HTA, CTA requires significant time and resources. Applied Cognitive Task Analysis (ACTA) is a streamlined version of CTA, providing the practitioner with a set of data extraction methods that are designed to support interventions, such as training programmes or work design recommendations (see Militello & Hutton, 1998). This technique was the most relevant for the current study.

2. Aim

The aim of the study was to identify the SA components required for kick detection by (1) producing a task description from technical information (access to well control manuals, attendance on a training course and Subject Matter Experts (SMEs)) and (2) apply the preliminary Drillers' SA model (Figure 1) to identify the SA components, using the Applied CTA method (ACTA; Militello & Hutton, 1998). After completion, this could determine if the Drillers' SA components were present and if there were additional cognitive skills not present in the Drillers' SA model.

3. Method

The ACTA of SA for kick detection was produced over a seven month period (April – September 2014) with three SMEs and the process is descibed below in Figure 2.

Insert Figure 2 approximatley here.

3.1. Expert feedback

Expert feedback was sought on the technical task description and later on the SA components (see section 3.4.) using a method adapted from Clark, Feldon, van Merrienboer, Yates and Early (2008) and Militello and Hutton (1998). Three SMEs were contacted through the sponsoring company and a drilling school. All were male with over 25 years' experience in the drilling industry. For practicality, feedback was given face to face from two SMEs and for one via email, with their feedback being used to refine the task description and cognitive steps.

3.2 Technical task description

As there are different steps for kick detection depending on the location of the well (e.g. on land or sub-sea well) and the activity (e.g. drilling, tripping or making a connection), the specific task of drilling a sub-sea well was selected as based upon the severe consequences of a kick on a sub-sea well (Ismail et al., 2014).

As outlined in Figure 2, three technical well control manuals from the sponsoring company and a well control school were consulted and the first author took part in a five day well control course. Feedback was then sought from three SMEs on the technical task description.

3.3 Experts disagree

A disagreement arose between the SMEs regarding what actions should be taken if a change in active pit volume was recognised (whether to take action to flow check or to take alternative actions e.g. check for mud transfer). The disagreement needed to be resolved to complete the CTA. Domain experts frequently disagree, having developed their own methods and mental processes for completing complex tasks, in some cases using different reasoning to solve the same problem (Shanteau, 2001; Weber, Mavin, Roth, Henriqson & Dekker, 2014). As it was not the researcher's position to comment on technical steps or industry guidelines, advice was sought from a further three SMEs, one of whom was from another drilling company and two were from an operating company, specifically regarding the active pit volume issue via email. The additional SMEs all independently supported the argument that the driller should flow check the well rather than take alternative actions and therefore this is represented in the ACTA account of SA for kick detection in Figure 3.

3.4. Identifying SA components

Once the technical task description was deemed to be accurate by the SMEs, the SA components in the technical description were identified. The Drillers' SA model (Roberts et al., 2015a), as well as the prior interview and observation data that the model was developed from, was used as the coding framework to identify the cognitive steps. These prior data consisted of 18 interviews with experienced drill crew and 24 hours of observations (live and in-vivo) of drill crew taking part in well control scenarios in a high fidelity simulator. For example, the coding framework included Drillers' SA components such as attending to the situation, gathering information and recognising cues. The SA components were identified for the full technical task description and given to three SMEs for feedback. The identification of the SA components for the entire task description produced the ACTA account of the cognitive components required for kick detection.

3.5 Final ACTA for kick detection

Feedback was then sought again from all three SMEs on the full ACTA of SA kick detection data. With regard to ensuring a level of objectivity to support the validity of the model, during the population of the task description with SA components, the researcher remained open to non-fitting cognitive components/steps and explicitly considered how her background and biases may impact on the production of the kick detection CTA, such as prior knowledge of well control procedures.

3.6 Further model evaluation

A supplementary aim was to evaluate the Drillers' SA model using Miles, Huberman and Saldana's (2014) guidance on testing the validity of qualitative models. As this was a further evaluation, the criterion was that the cognitive components of the Drillers' SA model should be present in the data. Consequently the Drillers' SA model was evaluated to determine if the key Drillers' SA components were present, if any additional aspects of drillers' SA not included in the model were present or if there were components that did not merit inclusion. Miles et al. (2014) recommend that expert feedback should be obtained to verify the CTA as was done for both the technical and SA steps in the CTA.

4. Results

The ACTA account of the SA components required for kick detection was produced as described above and is shown in Figure 3. It outlines the SA components for the technical steps in the task of identifying and responding to a kick indicator (including the associated decisions and actions.)

Insert Figure 3 approximately here or include a pertinent section for illustration (and make the whole kick detection CTA available as an e-appendix).

The ACTA for kick detection and frequency data shown in Table 1 illustrate that to recognise a kick indicator is present utilizes a similar process across all the indicators and action steps, namely recognising a cue from the environment, understanding its significance and anticipating the consequences of the indicator. Perceptual (total frequency = 73) and comprehension components (total frequency = 59) being more frequently identified than anticipation components (total frequency = 43). Meta-cognition had a low frequency count (total frequency = 2) which may be because the task analysis represents the ideal situation whereas meta-cognition was found to be associated with difficult, ambiguous or distracting situations (e.g. Sethumadhavan, 2011). However, it should be noted that the frequencies may relate to the weighting of the technical steps outlined in the course and manuals.

The results in Figure 3 and frequency data in Table 1 show that all the Drillers' SA model components were identified, no components were missed out or additional components identified. The ACTA provides a level of consistency with the previous interviews, observations and accident analysis (Roberts et al., 2015a, b), supporting triangulation and consequently tentatively supporting the prototype Drillers' SA model.

Insert Table 1 approximately here.

The perceptive skills of attending to the situation, such as the drilling parameters on the control screens, gathering information about the well state and surface activity (e.g. making calculations) and recognising relative changes in the drilling parameters (e.g. increase in the percentage of return flow from the well) were vital for the initial stages of kick detection, as reflected in the frequency data (level 1 SA). In some instances, the cues may be present in combination rather than isolation, requiring vigilance for change.

For changes in the drilling parameters to be understood as kick indicators requires their significance to be interpreted in the context of the driller's mental model (Level 2 SA). Comprehension that an influx or kick could be in progress occurred in collaboration with the driller's prior understanding of the situation, task specific mental picture, expectations and experiences. The number of times that mental pictures were identified in the ACTA (total frequency = 28) during both the kick indicator (frequency = 17) and action steps (frequency = 7) highlights the importance of accurately maintaining and updating the current on-task mental picture for subsequent cycles of SA, decision making and actions. It is likely that the on-task mental pictures would direct attention and cue recognition, strongly influence interpretation and would be utilized for mental simulation, supporting the functional relationships between the components.

Anticipation of how the situation may develop was vital for accurate decision making and taking the correct actions (e.g. to flow check) in conjunction mental simulations, such as what may be causing the kick indicator (e.g. the well has become underbalanced or a piece of equipment has failed) or mentally preparing a game plan of how to cope with the kick (e.g. using experience and procedures to prepare a plan should the well need to be killed). Anticipation could also guide subsequent understanding (e.g. estimating how long a mud transfer will impact on the active pit volume would influence comprehension of the situation) and vigilance for indicators (e.g. anticipating that a new formation is coming, may result in a heightened attention for any changes in rate of penetration).

Whilst sharing information and awareness between the driller and drill crew was not mentioned as frequently (total frequency = 8;), this reflects the procedure wherein the driller is instructed that the priority is to flow check or shut in, with calling other crew members as a secondary task. It is likely that sharing information would impact the driller's SA at all levels of SA, impacting on where attention is focused, the way that the situation is interpreted and how it is anticipated to progress.

5. Discussion

The ACTA account of SA components shown in Figure 3 specifically highlights the importance of SA in kick detection and maintaining well control for process safety (i.e. if a driller misses a kick indicator or fails to understand that an influx is occurring, this can result in a kick or even a blowout). The cognitive account provides valuable insight into how expert offshore drillers develop and maintain SA during kick detection by (1) explicitly outlining the critical SA requirements for kick identification and the subsequent actions of flow check and/or shutting in the well, building upon the general skills identified by Roberts et al.'s prior interview and observation study. It also provides indications of the weighting of these components for kick detection (e.g. the significant importance of cue detection and developing an accurate mental picture of the well state). (2) It tentatively supports the preliminary Drillers' SA model (Roberts et al., 2015a) and consequently supports the fit of Endsley's (1995) model in the relatively unexplored drilling domain. The ACTA reflects the SA skills identified in IOGP's (2014a) preliminary well operations CRM program, such as seeking relevant information, comprehension of the situation and risk status as well as foreseeing how the situation may develop. It also echoes their emphasis on monitoring for early kick detection and rapid, effective shut in (IOGP, 2012b). These findings extend existing knowledge on kick detection and can be used as the basis for effectively developing training interventions and work design recommendations for supporting drillers' SA and consequently safe working practices (see below).

The analysis reflects the findings of Sneddon et al.'s (2006) drilling accident analysis with perceptive skills frequently identified in the kick detection task, echoing the misperception errors they identified. The account also identified specific perceptual skills including monitoring, information gathering, vigilance and cue recognition that may have been involved in the analysed drilling accidents. In addition, the ACTA identified mental pictures and comprehension as important SA components for kick detection, reflecting the level 2 SA errors discussed by Sneddon et al. (2006) and Stanton and Wilson (2001), such as the use of poor or incorrect mental models. Previous research aiming to support drillers' SA through work design (e.g. Woodcock & Toy, 2011; Sawaryn et al., 2008) can be reinforced using the ACTA findings by identifying specific areas that can support drillers' SA (e.g. assisting cue recognition and supporting interpretation of cues; see below recommendations). The SA components in the account mirror those identified in other high-risk, high reliability domains, e.g. nuclear power control operators (Patrick, James, Ahmed & Halliday, 2006), aviation (Lini, Vallespir, Hourlier, Labat & Favier, 2013) and surgery (Wauben et al., 2011).

The ACTA provisionally suggests that Endsley's (1995) model of SA is suitable for the drilling domain. The task analysis in this study also shows the sharing of information and awareness between the crew members, suggesting a relationship between an individual driller's SA and the team (drill crew), which is reflected in a number of theories of team SA

(Endsley & Jones, 2011; Salas, Prince, Baker & Shrestha, 1995), as well as the more recent socio-technical theory of distributed situation awareness (Stanton et al., 2009;). Given that there is a continuing debate over the concept of SA (see special issues of *Cognition Technology & Work* (2015) and *Journal of Cognitive Engineering and Decision Making* (2015)) and whether SA models (e.g. Endsley's three level model) can be deductively validated (i.e. falsified), future research that experimentally tests the model would be valuable.

5.1 Limitations and future research

CTA methods are valuable for eliciting explicit and implicit knowledge from experts that can guide user-centred training programmes and work design recommendations (Jones, 2015; Militello & Hutton, 1998). However, conducting a CTA is time consuming and can be prone to researcher bias which has the potential to skew the data analysis (DeWalt & DeWalt, 2010). As it was not possible to have a second researcher complete the training, only one researcher produced the task description and coded the technical knowledge (e.g. training course and manuals), raising the issue of researcher bias. To address this issue, the researcher attempted to take an open-minded approach to the coding of the kick detection task, considering how potential expectations and biases may influence the analysis. As the SMEs had no prior knowledge of the SA models, they provided relatively objective feedback on the ACTA account. It should be noted that a study's objectives will determine the most appropriate TA methods to use, which can result in different outcomes. Further studies examining driller expertise may benefit from using and comparing multiple TA methods depending on study's intended deliverables.

The ACTA tentatively confirms Roberts et al.'s (2015b) Drillers' SA model and supports the fundamental information processing steps of recognising key indicators, interpreting that information and projecting of how the situation may develop, as outlined in Endsley's model. However, further testing will be required to examine the underlying components and linearity of the model. For example, sequential analysis could be used to test the sequence of the cognitive components (e.g. a sequential analysis; Cohen-Hatton, Butler & Honey, 2015).

A quantitative performance measure of driller SA which is less prone to research bias is an online simulated monitoring task that is being developed on the basis of the ACTA. It will have the potential to train and formatively assess drillers' cognitive skills (Roberts, Flin & Cleland, in prep). Drillers monitor well control scenarios on a computer with cue recognition, comprehension and decision making data being used as performance measures. A limitation of the SA kick detection account was that the influencing factors on SA were not examined; however the performance measure could be utilized to investigate factors such as expectations, distractions or work design, on aspects of SA. If successful, the tool could also been used to evaluate changes in drilling processes and drill cabin computer systems design.

The ACTA results could also be used as the basis of a hazard analysis to further examine human performance in relation to the safety critical task of well control, such as has been done using the petroleum Human Reliability Analysis tool (PetroHRA; Van De Merwe, Hogenboom, Rasmussen, Laumann & Gould, 2014). Further of the influencing factors and their impact on subsequent decision making and actions would be beneficial (e.g. how drilling software layout impacts on kick indicator recognition).

5.2 Recommendations

The findings extend existing knowledge on the SA components required for kick detection outlined by Roberts et al. (2015b) which can be used to form the basis of interventions such as effective training and work design recommendations that support the operator and consequently improve safety.

5.2.1 Accident Investigation

Despite research indicating the significant role that human factors play, in drilling and well intervention incidents (e.g. Roberts et al., 2015a; Sneddon et al., 2006; Smith, Kincannon, Lehnert, Wang & Larrañaga, 2013) as well as more broadly within the process industries (e.g. Antonovsky, Pollock & Straker, 2014; Broadribb, 2012; Cox, Carpenter & Ogle, 2014), there does not appear to be a standard tool for investigating these factors in drilling. The outcome of the ACTA could be used to support accident investigation as a method of understanding why operators missed kick indicators or took certain decisions, rather than blaming them for their actions (Dekker, 2015). For example, the Drillers' SA model has been used to provide insight into why the drill crew erroneously believed that the well was stable on the Deepwater Horizon drilling rig (Roberts et al., 2015a). The detailed analysis could be used to augment an existing well control investigation system (e.g. Manuele, 2014) or human factors investigation tool (e.g. Human Factors Investigation Tool, Gordon, Mearns & Flin, 2005) so as to increase the effectiveness of incident learning and prevent further incidents. Given the sparseness of evaluated human factors investigation tools in drilling, it may be worthwhile developing this for industry wide use, giving the opportunity for a standardised method of accident investigation and the possibility of comparison.

5.2.2 Situation Awareness Training

A number of simulation centres in the drilling industry already conduct training that includes technical, social and cognitive skills with debriefing on these aspects of performance. However, given the importance of maintaining kick detection for process safety, the detailed ACTA could be used to inform the training of specific SA scenario training for well control, as has been done in other (e.g. police fire arms training simulator, Saus et al., 2006). For example, drillers could take part in well control simulations (e.g. recognising kick indicators and making the decision to take no action, flow check or shut in) with debriefing feedback on their SA and performance. The training programme could also include information on specific SA skills for kick detection that would support safe working practices. This could include: how to interpret combinations of kick indicators; methods for gathering information effectively; or mentally simulating possible anticipated outcomes of different well control situations. The ACTA could also be used to supplement current human factors training such as that which has been conducted in other process industries (e.g. tactical decision games for emergency response training in refineries; Crichton & Flin, 2001). With limited time for training and as less experienced personnel are promoted, it may be advantageous to use the ACTA results to develop a new type of well control manual. It could include both technical guidance/steps and SA skills for kick detection, such as providing possible interpretations of indicators alongside technical guidance (e.g. as done for fire fighters, Crandall, Klein & Hoffman, 2006). The examination of other cognitive requirements necessary for effective kick detection would also be beneficial for non-technical skills training, particularly as the results highlights the vital role of decision making.

5.2.3 Drill Cabin & Software Design

The ACTA results can also be used to inform work design that supports drillers' SA, particularly for kick detection, advancing previous work design research (e.g. Woodcock & Toy, 2011). With the increase in automation in drilling systems, there is the opportunity to design software systems that support SA, rather than resulting in the performance problem of operators being out of the loop (Endsley & Kiris, 1995). For example, the drilling system display screens could be designed to support easy recognition of indicators, as emphasised in the ACTA (e.g. when a parameter goes above or below a threshold, the relevant section of the trend line could flash). The ergonomic layout of the information on the screens could be arranged to assist information gathering and support the best or ideal mental model (e.g. displaying readings on a 3D visual representation of the well that could be easily navigated). During flow checking and/or shutting in, the software could inform other crew members that the actions are taking place, rather than the driller having to make a phone call as outlined in the ACTA (e.g. either a message button or programming it to recognise a sequence of actions and automatically sending a message). It would certainly be advantageous that before any new software is installed, it is tested to examine its impact on the drillers' SA as is done in other high risk domains (e.g. nuclear power plant control rooms, Yang, Yang, Cheng, Jou & Chiou, 2012; maritime ship navigation, Sauer et al., 2002).

6. Conclusion

The ACTA specifically outlines the key SA components required during the safety critical task of kick detection, building upon Roberts et al.'s (2015a) Drillers' Situation Awareness model. The cognitive components required to successfully detect a kick were explicitly identified, including attending to the situation, recognising and interpreting the cue as a kick indicator, as well as anticipating that this may escalate into a kick or even a blowout. Flow checking and shutting in similarly require vigilant monitoring of the situation with a dynamic mental picture of down-hole and surface activities. Considering the increasing importance of SA for well control in maintaining process safety and the changing demographics of personnel, it would be highly valuable for the drilling industry to consider training and work design recommendations that support driller SA.

Acknowledgements

This article is based on a doctoral research project of the first author which was sponsored by an international drilling rig operator. The views presented are those of the authors and should not be taken to represent the position or policy of the sponsor. The authors wish to thank the industrial supervisor and the drilling experts for their contribution and patience, as well as Aberdeen Drilling School for allowing the first author to attend one of their well control courses.

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Table 1. Frequency of the components in the task analysis, kick indicator and action steps.

Theme	**No. of times occurred in kick indicators**	**No. of time occurred in actions (Flow check & Shut-in)**	**Total No. of times occurred in the task analysis**
Level 1 SA - Perception	**52**	**21**	**73**
1A. Attention	10	5	15
1A.1 Vigilance	8	5	13
1B. Gathering Information	24	4	28
1C. Cue Recognition	10	7	17
Level 2 SA - Comprehension	**52**	**15**	**59**
2A. Understanding	20	2	22
2A.1 Meta-cognition	2	0	2
2B. Mental Pictures	17	11	28
2C. Mental Models	6	1	7
Level 3 SA - Anticipation	**29**	**14**	**43**
3A. Projection	18	7	25
3A.1 Mental Simulation	7	2	9
3A.2 Preparation	4	5	9
Shared Information & Awareness	7	1	**8**

Figure 1. Roberts et al.'s (2015) Driller's Situation Awareness (DSA) model.

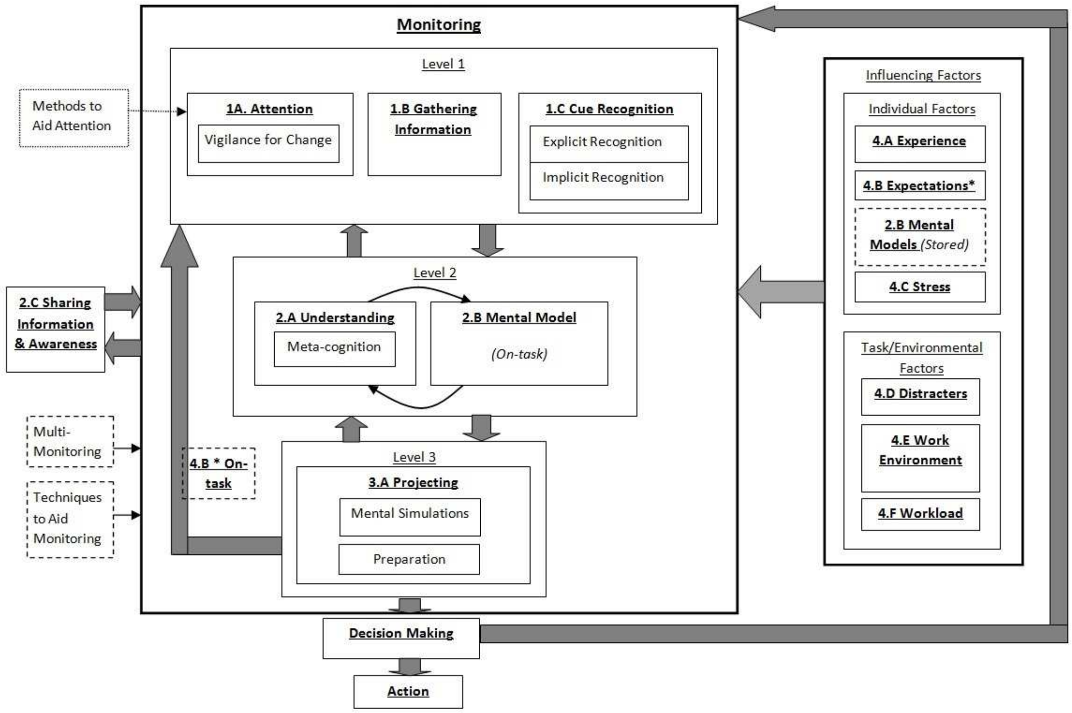

Figure 2. Method of producing the ACTA for kick detection. The thick arrows represent the process and the thin arrows represent the data used for each of the stages.

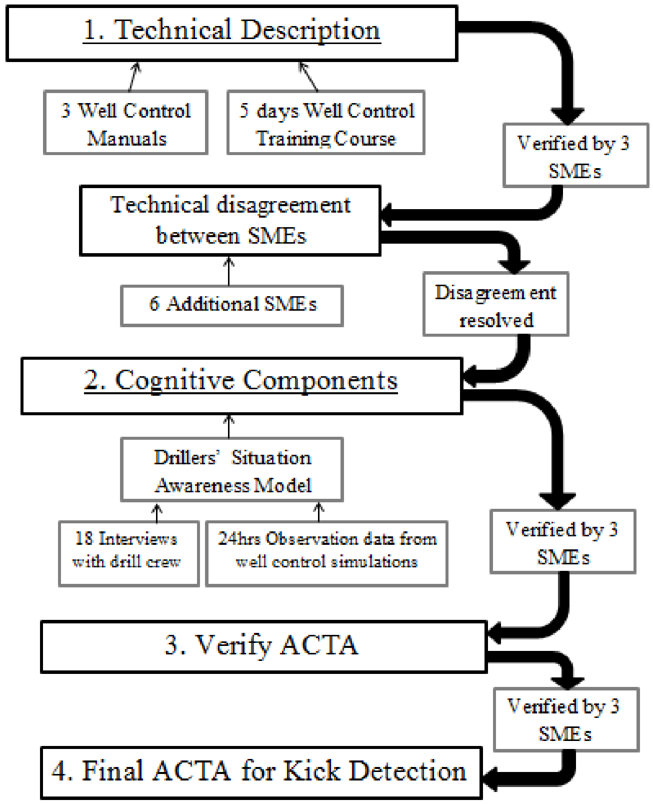

Figure 3. ACTA account of kick detection and subsequent actions of flow checking and shut-in with **technical steps**, **kick indicators**, the cognitive steps and associated cognitive components and *actions and decisions*.

1. **Observe kick indicator warning**
   1.1. **Change in flow rate**

Cognitive process:

- Attend to flow rate trend line or snap shot to gather information on the current state of the well

1.1.1. Increase in flow rate

- Recognised increase in flow rate:
- Interpret as a positive kick indicator
- Update current mental picture of the situation with increased flow rate information
- Anticipate that increase in flow rate could be the result of an influx occurring

1.1.2. Decrease in flow rate

- If decrease in flow rate is recognised:
- Interpret that losses could be occurring and as a kick indicator
- Update current mental picture of the situation with decreased flow rate information
- Anticipate that decrease in flow rate could be the result of losses occurring e.g. porous formation, ballooning or fractured formation and prepare for it e.g. reconsider pump strokes (circulating pressure), mud weight or LCM

1.1.3. Flow check *(Decision)*

1.1.4. Gauge rate of gain/loss

1.1.4.1. Check change in active pit volume

- Attend to active pit volume trend line or trend sheet
- Gather change in volume data from last X minutes (e.g. volume from 5 minutes ago and volume now)

1.1.4.2. Calculate rate of gain/loss – bbls/min *(Action)*

- Use readings gathered to calculate rate of gain/loss and interpret severity of gain/loss
- Update mental picture with rate of gain/loss
- Anticipate rate of gain/loss as situation progresses

1.2. Change in active pit volume

- Attend to active pit volume trend line or snap shot on drilling screens to gather information on the current state of the well

1.2.1. Gain in active pit volume

- Recognise increase in pit volume
- Confirm gain by checking screens, trend sheets or DFO's (Drilling Fluids Operator) (information gathering) *(Action)*
- Interpret cue as gain in the active pit volume and as a positive kick indicator
- Update current mental picture that gain is occurring
- Anticipate that gain could be the result of an influx

1.2.1.1. Flow check *(Decision)*

1.2.1.2. If flowing, shut-in.

- Interpret that the well is flowing and a kick is occurring
- Update current mental picture that an influx is occurring

1.2.1.3. If the well is static, continue monitoring and look for sources of gain *(Decision & Action)*

- Interpret that the gain is not caused by an influx
- Update current mental picture that an influx is not occurring
- Mentally simulate what could be causing the gain using experience and expectations and gather further information to find out e.g. a mud transfer?

1.2.1.4. Check for mud transfer

- Check memory for giving permission for mud transfers (expectations and current mental picture)
- Gather information about mud transfers by calling (or AD calling) DFO (Action)
- If mud transfer occurred:
  - Interpret gain as result of mud transfer into active system or error in transfers (using knowledge of the mud system in mental model)
  - Update current mental picture that mud transfer occurred
  - Estimate the quantity and for how long the mud transfer will affect the active pit volume, adjust volume totalizer as required (using information gathered and knowledge of mud system in mental model)
  - Update current mental picture with estimation of how the mud transfer will affect active pit volume
  - Continue monitoring whilst remaining vigilant for flow rate increase

-If no mud transfer has occurred or no surface justification for the pit gain, consider other options using stored mental models and experience

1.2.2. Loss in active pit volume

- Recognise decrease in pit volume
- Confirm decrease by checking the screen, trend sheets or DFO's notes (information gathering) *(Action)*
- Interpret cue as losses occurring in the active pit volume and as possible kick indicator
- Update current mental picture that losses are occurring in the formation
- Anticipate that this could result in loss in hydrostatic pressure and could result in a subsequent influx and mentally prepare for it e.g. reconsider mud weight, pump strokes and circulating pressure

1.2.2.1. Flow check *(Decision)*

1.2.2.2. If flowing, shut-in.

- Interpret as the well flowing and a kick is occurring
- Update current mental picture that an influx is occurring

***1.2.2.3.* If well is static, continue monitoring and look for sources of losses** *(Decision & Action)*

- Interpret that the losses are not caused by an influx
- Update current mental picture that an influx is not occurring
- Mentally simulate what could be causing losses using experience and expectations e.g. fractured formation, ballooning and gather additional information to find out *(Action)*

1.2.2.4. Check for leaks, spills, washout, etc.

- Use mental models of the mud system and rig to identify possible causes and locations of the losses (via mental simulation)
- If leaks found, interpret as leaks causing losses and update mental picture for where leaks and spills can occur
- If no leaks found, consider other options using stored mental models and experience

1.3. Drilling rate increases (Drilling Break)

- Attend to drilling rate trend sheet or snap shot on drilling screens
- Recognise increase in ROP
- Confirm increase by checking with logging unit (information gathering) *(Action)*
- Check to see whether change in formation is expected from shared information

- Interpret cue as drilling break
- Update current mental picture that drilling into new formation
- Anticipate that the new formation may contain higher pressures, porous formations and could result in influx

1.3.1. Drill further 3-5ft

1.3.2. Pick up off bottom with pumps still on

1.3.3. Flow check

1.3.3.1. If not flowing, continue drilling whilst monitoring unless instructed to circulate bottoms up.

- Remain vigilant for any further changes

1.4. Gas or water cut drilling fluid

1.4.1. Gas cut drilling fluid

- Attend to gas percentage (%) on screens to gather information on the current state of the well or mud logger calls to share this information
- Recognise increase in % or re-focus attention as result of alarm sounding (work environment)
- Confirm increase is above background gas trend line by attending to drilling screens (gathering information) or have AD check by calling mud logger *(Action)*
- Interpret that this is an early kick indicator
- Check whether the formation is porous (gathering information & expectation)
- Update current mental picture that gas has entered the wellbore
- Mentally simulate that the gas could be the result of drilling into formation containing gas, swabbing or the well going into under-balance and gather additional information *(Action)*

1.4.1.1. Other Kick indicator?

- Gather additional information about the situation to determine whether other kick indicators are present by attending to drilling screens

1.4.1.1.1. Yes – Flow check *(Decision)*

- If other kick indicator recognised:
- Interpret that a kick may be occurring and gas has entered the well bore

1.4.1.1.2. - No – Continue monitoring whilst drilling *(Decision)*

- If no other kick indicator recognised:
- Interpret that a kick is not in progress
- Update current mental picture that gas has entered the well bore but experience says that it is unlikely to reduce the bottom hole pressure substantially
- Anticipate that gas will expand as it is circulated up the well bore which may result in belching.
- Remain vigilant for any further changes with the expectation that drilled gas should only be present for the time taken to circulate out the cuttings if drilled gas.

1.4.1.2. Ensure de-gassing occurs to prevent re-circulation *(Action)*

- Gather information on the current % of gas in the returning mud *(Action)*

1.4.1.2.1. Ensure that degassers can cope with the level of gas returning

- Anticipate whether current amount/% of gas will be removed by degassers by comparing current % of gas in returning mud and working limit of the degasser.
- If unsure (meta-cognition) of working limit, gather information from crew members *(Action)*

1.4.1.2.2. **If not, circulate until the level of gas becomes acceptable** *(Decision & Action)*

- If % of gas in returning mud exceeds working limit of the degasser, take action to circulating rates until level acceptable

- Monitor % of gas in mud during circulation and remain vigilant for anticipated acceptable level of gas in mud.

1.4.1.2.3. Check whether the level of returning gas is caused by too fast a drilling rate

- Anticipate that drilling too fast could be causing the gas cut mud
- Attend to drilling rate on drilling screen and gather additional information on pre-determined rate
- Experience will also inform whether drilling rate is too fast for current task but if unsure seek assistance from Tool Pusher (meta-cognition & sharing information)

– Determine if rate is too fast (understanding)

1.4.1.2.3.1. If so, then drill at a controlled rate (so that the gas doesn't break out belching) *(Action)*

- Monitor % of gas for anticipated decrease after drilling rate reduced.
- Anticipate that drilling too fast could result in belching

1.4.2. Water cut drilling fluid

- Mud logger or mud engineer shares with driller that returning mud contains water (sharing information & awareness)
- Update current mental picture that water has entered the drilling fluid

- Mentally simulate that water could be leaking into the drilling fluid through from water in the formation
- Check for any expected porous formations or aquifers
- Anticipate that this could reduce mud weight, subsequent hydrostatic pressure and that an influx may be underway.
- Gather additional information about the flow rate, active pit volume and returning mud weight.

1.4.2.1. Check active flow rate 1. 1 and pit volume 1.2

1.4.2.2. Check mud weight for reduction

- Call Shaker Floorman to check for reduction in mud weight in mud returns and to call back promptly with a result (sharing information)
- Anticipate that the reduction in mud weight could affect hydrostatic pressure, resulting in an influx.
- Take action to determine where the water source is located *(Action)*
- Consider whether the mud weight should be increased *(Decision)*

1.5. Decrease in pump pressure or Increase in pump strokes

- Attend to pump pressure or pump strokes on drilling screens to gather information on the current state of the well
- Recognise decrease in circulating pressure or increase in pump strokes
- Interpret that decrease in pump pressure or increase in pump strokes could be the result of lighter hydrocarbons entering the well bore, reducing the circulating pressure or equipment failure e.g. mud pump or drill string failure.
- Anticipate that hydrocarbons may have entered the well bore and a kick may be occurring

1.5.1. Stop pumps *(Action)*

1.5.2. Flow check *(Decision)*

1.5.3. If static:

-Interpret that not experiencing an influx

1.5.3.1. Consider whether anything could be leaking in the down hole or surface equipment

-Mentally simulate what could be causing it (experience & stored mental models) e.g. a hole in the drill string or a washed out drill bit nozzle down hole or washed out valves, piston or liners on surface

-Have the crew check for washed out equipment and consider taking action for down hole equipment *(Action & Decision)*

- Remain vigilant for any further changes in pump strokes/pump pressure

1.6. - Hole not taking correct amount of fluid during tripping

- Before tripping calculate (preparation) the expected amount of fluid required to replace the removed pipe using trip sheets (work environment)
- Attend to trip tank volume (flow in versus flow out)
- Recognise that the hole is not taking the correct amount of fluid i.e. more or less than expected
- Interpret that something is going on in the well; either fluid is coming out from the formation or going into the formation
- Confirm that the correct amount of extra fluid was prepared beforehand (gathering information)
- Mentally simulate that something is occurring in the well, possibly an influx or swabbing.

1.6.1. Flow check *(Decision)*

1.6.2. Inform supervisors (secondary to flow check) *(Action)*

1.6.3. If not flowing:

- Remain vigilant for any further indicators during tripping

1.6.3.1. Running in, return in the hole to bottom

1.6.3.1.1. Circulate bottoms up

1.6.3.2. Pulling out, return to bottom and circulate bottoms up (remain vigilant)

1.7. Heaving Shale

1.7.1. Have Mudlogger check for increase in volume or size of cuttings and cavings

- Mud logger calls driller to share information on cuttings or cavings
- Interpret that the heaving shale could indicate abnormal pressure zones
- Gather additional information on whether this is expected
- Anticipate that this could be an indicator of an underbalanced well

1.7.2. Check for other kick indicators and remain aware of cuttings loading up the annulus

- Gather additional information on the situation and remain vigilant for further indicators

2. Flow check (Action)

2.1. Pick up off bottom and space out string *(Action)*

- Utilize mental picture of the string and joints in the well located near the BOP to calculate the position of the joints for spacing out
- Update current mental picture of the position of the drilling string in the BOP

2.2. Shut pumps down and maintain slow rotation *(Action)*

- Update mental picture that pumps off
- Prepare for flow check by gathering finger printing graphs (if HPHT well) to provide additional information on expected flow back

2.3. Utilize finger printing graphs if available

2.4. Line up returns to trip tank *(Action)*

- Utilize stored mental model of the pipe system to line up to trip tank to effectively monitor flow

2.5. Switch on trip tank pump

2.6. Record time, active pit and trip tank volume

2.7. Record time and trip tank volume every minute for minimum for 15 minutes

- Attend to trip tank volume and monitor flow over shale shakers
- Update current mental picture of any changes as they occur
- Remain vigilant for any changes
- Remove any distractions and delegate secondary tasks to other crew members
- Mentally prepare to shut in should flow be recognized

2.8. Inform mud loggers, DSV and Drilling Section Leader/Toolpusher *(Action)*

- Share information with drill crew members, particularly mud logger that flow checking is occurring (or have the AD call)

2.9. Flow?

2.9.1. If flowing – stop rotation and go to shut in 3. *(Decision & Action)*

- Recognise flow from trip tank volume increase or flow over shale shakers
- Interpret that the well is flowing and update mental picture that experiencing a kick
- Anticipate that this kick could result in a blowout

2.9.2. If no increase in flow, monitor for minimum of 15 minutes, or as long as deemed necessary. (30 minutes if HPHT)

- Remain vigilant for indications that the well is flowing
- If flow is recognised, interpret that the well is flowing and update current mental picture that experiencing a kick
- Anticipate that kick could result in a blowout

2.9.2.1. If still no flow, cautiously resume drilling whilst monitoring (remain vigilant) *(Decision & Action)*

- Remain vigilant for further kick indicators whilst drilling
- Update mental picture that well was flow checked but did not flow (experience)
- Mentally simulate/discuss why these indicators were originally seen to understand what happened

3. Shut in (hard)

3.1. Close annular preventer *(Action)*

3.2. Open choke HCR valve against a fully closed choke (if using the hard shut-in procedure) *(Action)*

- Check that choke fully closed beforehand (gathering information)

3.3. Read shut in DPP and CSG pressure every minute until stabilised.

- Attend to DPP and CSG pressure on screens and remain vigilant for pressures stabilising (cue recognition)
- Once stabilised, update mental picture of shut in pressures for completing well kill sheets (mental preparation)

3.3.1. If float installed, establish drill pipe pressure

- Attend to pump pressure on screens and remain vigilant for small decrease (cue recognition)

3.3.1.1. Pumping down the string until a small decrease in pump pressure is seen *(Action)*

- Once small decrease recognised, update mental picture of SIDPP for completing kill sheets (preparation)

3.3.1.2. Note the pressure at this point as the SIDPP

3.4. If RIH with casing confirm closing pressure on annular according to collapse pressure of the CSG *(Action)*

- Gather/calculate collapse pressure of the CSG
- Attend to annular closing pressure during adjustment according to CSG collapse pressure (cue recognition)

3.5. Adjust motion compensator to string weight (floaters only) *(Action)*

- Anticipate that the motion compensator will need to be adjusted for change in string weight

3.6. Ensure space out of string

- Gather additional information and utilize current mental picture to check that joints are not in the BOP

3.7. Close middle pipe ram and equalise pressure prior to open annular preventer (floaters only) *(Action)*

3.8. Hang off drill pipe on upper pipe rams using motion compensator (floaters only) *(Action)*

- Update current mental picture that upper pipe rams closed

3.9. Monitor riser on trip tank (floaters only)

- Attend to the trip tank volume and monitor for changes in volume

3.10. Well kill procedure – drillers method preferred but other options can be used if the situation requires *(Decision)*

- Interpret that the well is now shut in
- Mentally simulate and prepare for the well kill procedure

Highlights:

1. An Applied Cognitive Task Analysis (ACTA) identified the cognitive steps required for expert offshore drillers to develop and maintain Situation Awareness (SA) for the well control task of kick detection.
2. The Driller Situation Awareness model, developed from interviews and observations, was utilized to identify the cognitive steps in the ACTA, and was found to be a suitable fit for the drilling domain.
3. The cognitive components required to successfully detect and respond to a kick were explicitly identified: vigilance, recognising and interpreting the cue as a kick indicator in conjunction with a dynamic mental picture down-hole and surface activities, as well as anticipating that this may escalate into a kick or even a blowout.
4. The ACTA account highlights the importance of SA for kick detection and maintaining well control. The findings can be used to inform training and work design recommendations that support driller SA and consequently, supporting process safety in drilling operations.