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'Everything was fine': an analysis of the drill crew's situation awareness on Deepwater Horizon.

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“Everything was fine”*: An analysis of the drill crew's situation awareness on Deepwater Horizon*

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A r t i c l e I n f o

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A b s t r a c t

Purpose: Investigation reports into the Deepwater Horizon drilling rig disaster identified issues with the drill crew's situation awareness (SA). The aim was to (1) apply the Driller's Situation Awareness (DSA) model to the cognitive data extracted from accident reports from this event to determine if it could help to explain why the crew erroneously concluded that the well was stable, which would (2) provide a preliminary evaluation of the model's validity.
Method: The DSA model was used for a content analysis of the SA components in the accounts of the crew's actions during two Negative Pressure Tests (NPT), in the hours before the blowout.
Results: The analysis provided (1) insight into the crew's likely cognitive processes before the blowout. In particular, it revealed issues with their interpretation and mental models of the well state, as well as possible influencing factors including expectation, distraction and experience, emphasising the impact that SA can have on process safety. The categorisation has (2) initially suggested that the DSA model does contain the appropriate components.
Limitations: There are limited first hand reports of this event and thus cognitive processes have to be inferred with a degree of caution.
Practical implications: The findings give a preliminary validation of the DSA model for further use in training and in investigation of well control events. Recommendations based on the findings are offered for assisting driller SA and consequently, for supporting safe and efficient drilling operations. There is also the opportunity to adapt the DSA model and apply the recommendations from the analysis to similar monitoring positions, where SA is essential, within the process industries.

Keywords: Deepwater Horizon Offshore drill crew Situation awareness Accident analysis Process safety

* Testimony from R. Ezell on his call with J. Anderson at 9.20pm about the negative pressure test. (BP Trial Proceeding Transcript, p.1682) and (Hearing before the Deepwater Horizon Joint Investigation Team, May 28, 2010, p.282).

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1. *Introduction*

Human failures in relation to monitoring and situation awareness of plant status have been identified across the process industries (e.g. chemical plants, Shin, 2014; gas platforms and gas processing plants, Antonovsky et al., 2014). For example, operators appeared to have failed to monitor the level of chemicals in a bulk storage tank and to recognise that it was overfilling, which resulted in a vapour cloud that ignited at the Buncefield fuel depot, causing a huge explosion (Atkinson et al., 2014). Failures to monitor crucial indicators were also identified in the Texas City disaster, such as the increased pressure in the raffinate splitter and safety relief systems (Khan and Amyotte, 2007). In the offshore drilling industry, the same cognitive skills are required for the drill crew that are building the wells for oil and gas extraction. This paper examines the role of the drill crew's situation awareness in the *Deepwater Horizon* drilling rig disaster.

On April 20th 2010, the *Deepwater Horizon* drilling rig was preparing to temporarily abandon the Macondo well, in the Gulf of Mexico, when it experienced a significant blowout of hydrocarbons. This resulted in the death of 11 crew members, the rig's destruction and the worst oil spill in US history. The accident cost the operating company, BP, an estimated $43bn, excluding potential fines for gross negligence (Macalister, 2014). The human and environmental costs of *Deepwater Horizon* make it critical to understand what happened in order to advise how best to ensure a similar disaster does not happen in the future. We applied our Driller's Situation Awareness (DSA) model (Roberts et al., 2015) on cognitive data extracted from a specific period in the accident reports, to test this model and to investigate why the crew erroneously concluded that the well was stable. As operators do not intend to have inaccurate SA or to take the wrong decision, considering why an action seemed like the right thing to do, rather than focusing on what operators did wrong, can be valuable for avoiding some of the pitfalls of hindsight bias (Dekker, 2007, 2009).

A brief account of the relevant phase (Negative Pressure Test) of the *Deepwater Horizon* disaster and why it was selected for detailed analysis follows, then we introduce the concept of situation awareness and explain how it has been previously studied in the drilling industry.

1.1. *Investigation into Deepwater Horizon*

In the wake of the disaster, numerous investigation reports examined the events leading up to the blowout and the subsequent response (see Table 1). These highlighted issues associated with technical decision making, management failures within BP, the overarching regulatory framework, and human factors. This paper focuses on the last of these issues.

As in all high risk domains, the system operators play a key role in protecting or endangering technical and human assets on the operational site. In drilling tasks, accurate monitoring of the well's state and recognition of “kick” indicators (when well control is lost, an influx of fluids into the well can occur, referred to as a “kick”) are vital for effective responses to reduce the risk of adverse consequences such as a blowout (API, 2006; Fraser et al., 2014). Well control and kick detection act as essential process safety barriers. The drill crew's role in the Deepwater Horizon accident is indicated in the Report to the President (2011), which states that “the failure to properly conduct and interpret the negative pressure test (NPT) was a major contributing factor to the blowout” (p.119). The crew erroneously believed the well was stable when it was not, missing and/or misinterpreting crucial cues and hence not being fully aware of what was going wrong down the well. Therefore, the crew did not have an accurate situation awareness of the well state. Consequently, the NPT phase of the event was selected for detailed analysis.

This test (NPT) is a means of checking the integrity of a well's “bottom hole” cement job, designed to prevent hydrocarbons leaking into the wellbore when the well is temporarily abandoned. The NPT could be considered as a type of situation awareness tool with which to gather information on the well and assess its stability. It requires a relatively interactive role from the drill crew compared to the monitoring components of everyday drilling tasks in the drill cabin. The methods used to minimise the potential for a kick (see below) or blowout, as occurred on Deepwater Horizon (and to regain control of the well in such an event) are known as well control (IADC, 2015). These include the hydrostatic pressure produced from the column of drilling fluid, equipment (e.g. the Blow-Out Preventer) and procedures (e.g. flow monitoring).

1.2. Situation awareness

Situation Awareness (SA) is the cognitive skill of maintaining awareness of the work environment, to understand the information that it holds, and to predict how situations will develop (Endsley, 1995, 2015). Inaccurate SA can lead to poor decision making and unnecessary risk taking, increasing the likelihood of an accident (Stanton et al., 2001). A number of SA theories have been proposed (e.g., Smith and Hancock, 1995; Wickens, 2002; Stanton et al., 2009). However, Endsley's (1995) three level model of SA dominates the field, being frequently applied in higher risk domains (e.g. nuclear power plants, Lee et al., 2012; maritime, Saus et al., 2012). She describes SA as a cognitive product of three hierarchical levels, perception (Level 1), comprehension (Level 2) and prediction (Level 3), identifying task and environmental factors, as well as individual factors that can influence it.

1.3. Situation awareness in drilling incidents

The role of SA has been identified in drilling incidents, including the blowout on the *West Atlas* rig on the Montara well, which caused a substantial oil spill in the Timian Sea (Montara Report, 2010) and the sinking of the Petrobras P-36 drilling rig which killed 11 men (Woodcock and Toy, 2011; USEPA, 2001). Poor monitoring and misinterpretation of crucial kick indicators were also involved in the Bardolino incident in the North Sea which occurred only four months prior to Deepwater Horizon (Energy and Climate Change Committee, 2010). Situation awareness has also been associated with numerous small scale accidents and personal injuries (Lootz et al., 2013; Hare and Johnson, 2009). Furthermore, offshore installation managers reported that loss of care and attention was one of the main causes of accidents on their production platforms and drilling rigs (O'Dea and Flin, 1998).

Cognitive factors have also been identified in relation to *Deepwater Horizon*. Reader and O'Connor (2014) applied a non-technical skills framework, including SA, to examine the blowout. They highlighted several cognitive factors (e.g. confirmation bias and expectation). Similarly, Hopkins (2012) noted the crew's inaccurate mental model of the situation which was fed by their assumptions. While useful in emphasising the importance of SA in Deepwater Horizon, these studies did not analyse the situation awareness of the drill crew explicitly or in depth.

1.4. Research on situation awareness in drilling

Issues in relation to drillers' concentration, inadequate hand-offs, poorly designed displays, difficulties with interpretation of information, inaccuracies in analysis and omitting to monitor data have been identified in research studies (Stanton and Wilson, 2001; Det Norske Veritas, 2007; Sawaryn et al., 2008). Sneddon et al., (2006) utilized accident analysis and interviews, and found that 67% of SA errors in drilling were classified as level 1 errors, as per Endsley's (1995) model of SA, with the majority of these relating to failure to monitor or observe data. A questionnaire study of drilling personnel in the North Sea found that higher levels of stress, sleep disruption and fatigue are significantly associated with lower levels of SA, and lower SA was related to more unsafe behaviour and increased work accidents (Sneddon et al., 2013). Thus these results highlighted the impact that SA errors can have on safety.

Table 1
Sources used to develop the timeline and analyses.

Sources
Bly Report, BP. (2010). Deepwater Horizon Accident Investigation Report.
Chief Counsel's Report. (2011). Macondo; The gulf oil disaster.
Deepwater Horizon Study Group (2011). Final report on the investigation of the Macondo well blowout.
National Academy of Engineering (2011). Macondo Well e Deepwater Horizon Blowout: Lessons for Offshore Drilling Safety.
OLF (2012). Deepwater Horizon lessons learned and follow-up.
Report to the President (2011). National Commission on the Deepwater Horizon Oil Spill and Offshore Drilling.
The Joint United States Coast Guard/Bureau of Ocean Energy Management Investigation (2010). USCG/MMS Marine Board investigation into the marine casualty, explosion, fire, pollution and sinking of the mobile offshore drilling unit Deepwater Horizon, with loss of life in the Gulf of Mexico 21e22 April 2010.
Transocean Investigation Report (2011). Macondo well incident. Volume 1 & 2.
U.S. Chemical Safety and Hazard Investigation Board (2014). Explosion and fire at the Macondo well. Investigation Report Volume 1 & 2. Report No. 2010-10-I-OS.
United States of America V. BP Exploration & Production Inc. et al. 2:10-CV-4536 (2013). Transcripts of nonjury trial proceedings heard before the honourable Carl J. Barbier United States District Judge. (R. Ezell, p1653ep.1813; J. Keith, p.3488e3726).

We used an analysis of well control simulator observations and interviews with drill crew members to develop the prototype Driller's Situation Awareness (DSA) framework (Roberts et al., 2015) (see Fig. 1), which is based upon Endsley's (1995) three level model. As SA research in drilling has been limited, this empirically based model provided preliminary understanding of the cognitive components associated with offshore drillers' development and maintenance of SA during well control and identifies key influencing factors.

The DSA model portrays a cyclic process of information gathering and cue recognition, from the task environment and other crew members, to form an understanding of the well state and anticipate how it may develop. Specific SA skills such as focussing on the drilling screens or activity on the drill floor, obtaining information from multiple sources (e.g. phone calls, asking questions, calculations and handovers) and recognizing a pattern from available indicators were found to be important for the driller to successfully build a mental model of the well state. As in other domains, comprehension is founded on mental models, expectations and experience, as well as sharing of information between crew members. Anticipation is achieved through mental visualizations of how the situation may develop and this can be based on actions e.g. mentally preparing a game plan or making required calculations. Influencing factors consisted of distraction, experience, expectation, coping with stressful or demanding situations, work environment and workload.

2. Objectives

The objective of this study was to (1) apply the prototype DSA model (Fig. 1) to the accounts of the drill crew's situation awareness during the *Deepwater Horizon* NPT event to determine if this could explain why the crew erroneously concluded that the well was stable, which would (2) act as a preliminary evaluation of the model's validity.

3. Method

The investigation reports and court transcripts that focussed on the drill crew's actions, were the basis for the analysis (see Table 1). A content analysis of the NPT phase of these reports was undertaken, following Miles et al., (2014) guidance on testing the validity of qualitative models. As this was a preliminary evaluation, the only criterion was that the cognitive components of the DSA model should be present in the data. This accident analysis should also identify any additional aspects of drillers' SA not represented, and components which do not merit inclusion, in the model. Miles et al. recommended that expert feedback should be obtained to verify this data analysis.

As for any major event, each document in Table 1 has a particular focus and each may have inherent biases associated with the chosen focus. Where contradictions occurred, the Chief Counsel's Report (2011) was given precedence, as it provided the most detail and did not take a specific legal stance. All the sources were taken at face value. Due to the nature of the event and the absence of evidence from key workers who were killed in the accident, the mental processes outlined are inferred from the survivors' accounts. However, first hand evidence is included where available (e.g. R. Ezell's trial proceeding transcript).

First, as advised for systematic accident analysis (Salmon et al., 2011), a timeline featuring the key personnel (see Table 2) was produced for the final shift of the drill crew before the blowout occurred on 20th April, 11am to 9.52pm.

Secondly, the DSA framework was applied to the accounts of the NPT time frame of 3pm~8pm which encompassed preparation for the tests, their execution and the eventual decision that the NPT was successful. This involved reading each report for every step of the event to identify the SA components and influencing factors, then coding the text using the DSA framework. This produced an adapted form of a SA requirements table (Endsley, 1993). It was verified by a drilling expert who was familiar with the event.

For the first NPT (5pme~6.45pm), two of the main reports, the Chief Counsel's Report and Report to the President, were cross-coded for this time frame, using coding rules for content analysis (Mayring, 2004). A second coder was trained in using the coding scheme and a basic understanding of the drill crew roles by the first coder (the first author). Whilst there was a possibility of transferring the first coder's biases and expectations during the training period, the coding of non-fitting data was strongly emphasized. Both coders practised using the coding scheme together on a section of the event not included in the analysis (3pm~4pm), after which they separately coded the reports for the first NPT. Cohen's (1960) kappa coefficient was found to be acceptable (0.738) (Fleiss, 1981). The remaining hours of the event were coded by the first author.

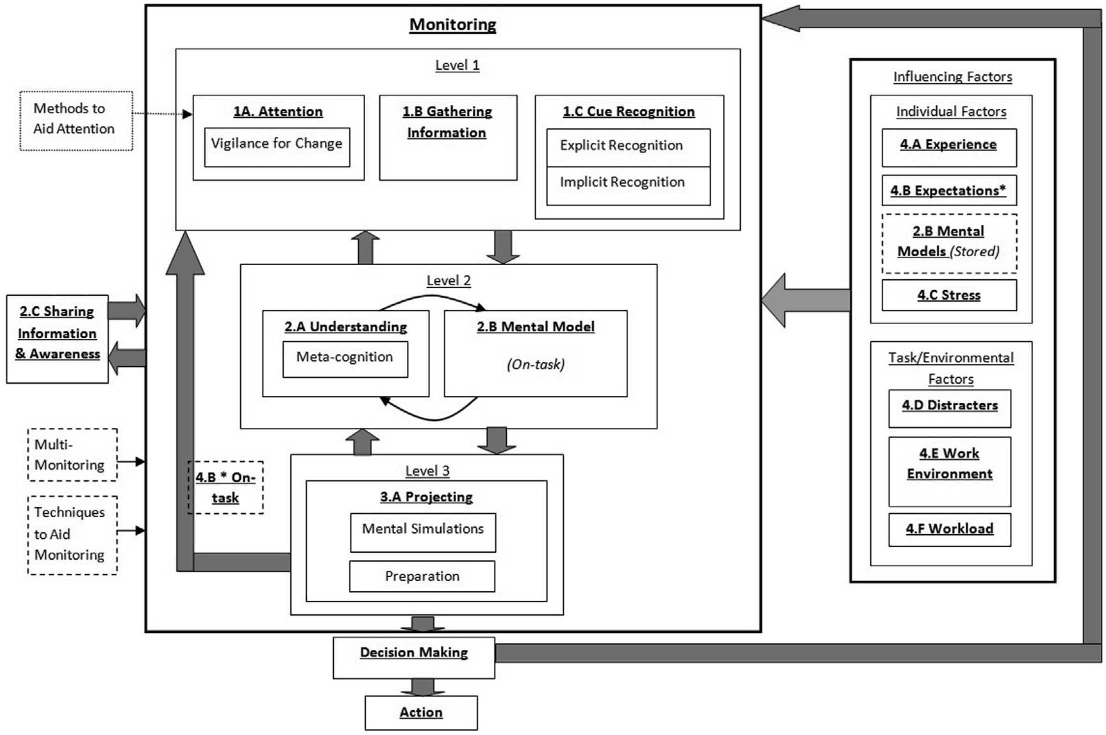

Fig. 1. Roberts et al.'s (2015) Driller's Situation Awareness (DSA) model.

4. Results

4.1. *Analysis of the drill crew's SA during the negative pressure tests*

A narrative of the drill crew's likely cognitive processes relating to the DSA framework during the NPTs was extracted from the material (see Table 3). A more detailed description of the development of the crew's situation awareness throughout the event and the influencing factors (shown in parenthesis), including experience, expectations, stored mental models, stress, distracters, work environment and workload is provided below. The relevant components of the DSA model are noted in bold for each stage. (See Appendix A for abbreviations and glossary.)

4.1.1. *Preparation for NPT*

The drill crew prepared for the first NPT by conducting a pre-job safety meeting and preparing the well for the NPT by pumping a specialised fluid (called a spacer), to above the BOP annular.

The positive pressure test for the cement job of the casing conducted earlier in the shift (approximately 11am), had been deemed a success, thus providing a strong expectation that the forthcoming negative pressure test would also be successful (expectations). It is unclear whether the drill crew were aware of the BP well site leaders' concerns about prior losses recorded during the cement job (Report to the President, 2011, p.118; Transocean Investigation Report, 2011, p.94; level 1 SA). The spacer was an unusually large volume (424bbls) and made from left over, heavy Lost Circulation Materials (LCM), making it less likely that the crew had any substantial experience of circulating such a large volume and density of spacer into position (experience). Furthermore, whilst the crew may have been aware of the difficulties with the centralisers and multiple attempts at converting the float-collar during the cement job on the previous day, it is unclear whether they incorporated this information into their understanding of the situation (mental model) or anticipated the impact that this may have had on the NPT (anticipation). Rather it appears that they viewed the previous problems in isolation from the NPT and the crew failed to anticipate their impact (R. Ezell Trial Proceeding Testimony, p.1668; level 1 SA).

It has been suggested that during the 3pm pre-job safety meeting, led by the mud engineer, whilst a general overview of the displacement procedure and negative pressure test was given (sharing information &

expectations; Chief Counsel's Report, 2011, p.149), there was no mention of any contingency procedure should the test fail, thus priming the crew that the test would pass (expectation; Chief Counsel's Report, p. 120, p.163; e.g. Doyen et al., 2012). Consequently, the drill crew may not have included these concerns in their on-task mental model (level 2 SA), not recognised the significance of conducting the negative pressure test (level 2 SA) or considering the lack of specific details, had not fully understood the NPT procedure (work environment impact on level 2 SA), potentially impacting on their SA throughout the task to come. It should also be noted that some members in the crew were close to the end of their stay offshore, making them more likely to be affected by fatigue (Burke et al., 2003). In addition, there was commercial pressure to complete the temporary abandonment procedure, which was already six weeks behind schedule, racking up considerable costs for BP (Deepwater Horizon Study Group, 2011). For example, the setbacks on the Macondo well were putting BP's more lucrative Kaskida well's licence in jeopardy by delaying it (Chief Counsel's Report, 2011, p. 354). A number of crew were also waiting to move onto their next jobs; for example, the Transocean tool pusher Jason Anderson had already been assigned to his next job on which he had been promoted to senior tool pusher (R. Ezell trial proceeding transcript, p.1737). This may have led the crew to experience time pressure which may have impacted on their SA and decision making (Sarter and Schroeder, 2001; Wickens, 2002).

Table 2
Key figures involved in the final shift and NPT including role, name and company.

Role	Name	Company
Assistant driller (AD)	Donald Clark	Transocean
Assistant driller (AD)	Stephen Curtis	Transocean
Cementer	Chris Haire	Halliburton
Driller	Dewey Revette	Transocean
Mud engineer	Gordon Jones	M-I Swaco
Mud engineer	Leo Linder	M-I Swaco
Mud engineer	Greg Meche	M-I Swaco
Mud logger	Cathleena Willis	Sperry Drilling
Mud logger	Joseph Keith	Sperry Drilling
Offshore installation manager	Jimmy Harrell	Transocean
Onshore senior drilling engineer	Mark Hafle	BP
Senior tool pusher (senior supervisor)	Randy Ezell	Transocean
Tool pusher (supervisor)	Jason Anderson	Transocean
Tool pusher (supervisor)	Wyman Wheeler	Transocean
Trainee well site leader (company representative on the rig)	Lee Lambert	BP
Well site leader (company representative on the rig)	Bob Kaluza	BP
Well site leader (company representative on the rig)	Don Vidrine	BP

Table 3
The timeline and associated situation awareness stages and influencing factors. Note: a row represents a key aspect of the event so may include more than one SA cycle.

Event e negative pressure test	Information available (Level 1 SA)	Crew interpretation/ understanding (Level 2 SA)	Any predictions made? (Level 3 SA)	Influencing factors (PSFs)
~3pm e Pre-job safety meeting led by the mud engineer with the well site leader present.	General displacement procedure and NPT information but no contingency procedure should the test fail. (CCR, p.163).	Unclear how fully the crew understood the procedure for conducting NPT. Crew's mental model was likely missing information about concerns during the cement job and risks associated with NPT. The well site leader “wasn't really clear on the neg[ative] test procedure.” (CCR, p.163, 120).	Overall anticipation of the coming displacement procedure but did not appear to include predicted bleed off volumes or how to interpret the readings.	Expectations about the coming shift with a strong emphasis that the NPT would pass. Lack of clarity on the procedures could have made understanding the coming task difficult (work environment). Crew nearly at the end of three week stay offshore (fatigue). Pressure to complete the job (workload).
3.04pme3.56pm e The driller pumped seawater into the boost, choke and kill lines to displace mud.	1200psi on the kill line with the pump strokes and volumes for pumping into boost, choke and kill lines.	Update mental model that the boost, choke and kill lines now contain seawater, not mud and that there is still 1200psi on the kill line.	The driller anticipated that the boost would be used for boosting the pumping of the mud during the displacement procedure making preparations to filli it with seawater .	*Stored mental models* of the well, equipment and mud system would have been utilized for updating the mental model.
~3.56e4.53pm e Pumped spacer followed by fresh water and seawater to displace ~3,300 ft of mud so that the spacer was above the BOP for conducting the NPT. Note: CCR ¼ Chief Counsel's Report (2011)	Pressure readings, pump strokes and volumes for pumping 424bbls of 16.0ppg spacer followed by 30bbls of fresh water and 352bbls of seawater at 8.6ppg to displace 14.17ppg mud. Unclear if crew were made aware of the characteristics of the spacer.	Updating mental model during displacement process of locations of different fluids in drill pipe, well bore and riser. Final mental model showing the spacer as 12 ft above the BOP with mud above it and seawater below it to 8.367 ft with the remainder of the well bore containing mud to bottom hole. Unclear if they recognised that the unusually large, heavy LCM spacer took considerable time to pump down.	Should the importance of the spacer characteristics not be understood, it is less likely that it would be anticipated that any of the spacer would have fallen back through the BOP. Or that this action would influence the subsequent NPT.	Unlikely that the crew had any substantial *experience* with dealing with such a large or heavy spacer. (CCR, p.150) Unloading of mud onto the Bankston ship between 3.03pm and 5.10pm will have made it difficult to monitor returning mud volumes (*work environment*).
4pme6pm e Simultaneous operations occurring including the cleaning of the trip tank preparing for the cement plug and bleeding off the riser tensioners.	Drill crew were made aware that these other operations could affect volume and flow metre readings.	Updating the mental model that these operations were going on during this time frame.		On-shift mud logger had concerns that these operations would affect her ability to monitor the return mud flow *(work environment)*. Preparation for the cement plug would give the *expectation* that the negative pressure test was going to pass.
4.53pm e The driller closed the annular but it was ~700psi higher than expected.	Drill pipe pressure 2,325psi when annular closed.	Interpretation of closed drill pipe pressure would have been skewed without an expected calculated reading to compare it to, perhaps resulting in the significance being missed.	No calculation of the anticipated closed drill pipe pressure.	
The driller bled off the pressure on drill pipe to equalise with kill line (KL) at 1,250psi. On opening them, the Kill Line Pressure (KLP) decreased and the Drill Pipe Pressure (DPP) increased simultaneously.	When the KL was opened, pressure decreased to 645psi but the DPP increased to 1,350psi (crew/ well site leaders' discussion of the readings).	The current mental model with knowledge about the U-tube effect should have shown that the DPP and KLP should match if going into same fluid. Well site leaders appear to have recognised this, showing concerns about the readings. The crew appear to have stuck to the interpretation that the spacer was still above the BOP and that the well was correctly set up for the NPT, failing to accurately interpret the readings.	Likely failed to anticipate the consequences of these readings on the well or NPT and no remedial actions were taken, such as circulating up to ensure no spacer was left below the BOP.	*Stored mental models* about the U-tube effect appear not to have been included. The *complexity* of the mental model may have influenced the accuracy of the current mental model. Appear to have stuck to their *expectation* that the spacer was above the BOP, influencing the interpretation of the readings.
5pm e Start NPT by shutting annular preventer in BOP and opening DP to bleed off pressure with flow during bleed off. When closed pressure builds up over 6 min.	When the DP was opened the pressure was 260psi and closed 1,262psi with pressure building up over 6 min. Witnesses have suggested that there was ~23bbls of flow during the bleed off (CCR, p.153).	Unable to bleed the pressure down to 0psi with some bleed off. The pressure then continued to build up on the drill pipe once it had been closed in. Failed to interpret the readings as an unsuccessful NPT or the significance of the short amount of time taken for the pressure to build back up.	No calculations were prepared for the amount of acceptable bleed off making subsequent interpretation inaccurate.	The riser leak may have *distracted* the crew during their interpretation process.
5.10pm e The crew notice that the level of fluid in the riser was falling, looking down the rotary	Riser volume is falling.	The riser appears to have been leaking and crew were trying to gauge how much had leaked.	Unclear whether they anticipated the effect of the spacer leaking below the annular on any	Problem of riser leak may have *distracted* attention away from the previous negative pressure test.

(*continued on next page*)

Table 3 (*continued*)

Event **e** negative pressure test	Information available (Level 1 SA)	Crew interpretation/ understanding (Level 2 SA)	Any predictions made? (Level 3 SA)	Influencing factors (PSFs)
table with a flashlight to see how much fluid was missing.		Unclear whether their mental model was updated to include the leak.	subsequent pressure readings/ tests.	
~5.20pm **e** Drillers' cabin becomes crowded with people in anticipation of the 6pm shift change and visiting BP and Transocean executives. The OIM instructed the crew to tighten the annular seal around the DP with Wheeler (on shift TP) adding 20**e**25bbls of mud to the riser which then remained static. The readings are discussed and the well site leader interprets them as a riser leak and the tool pusher interpreted as a well leak problem.	The volume in the riser is visibly dropping. The annular is tightened with approximately 20 **e**25bbls added to the riser. The riser volume is then static.	The crew appear confused suggesting that they were having difficulty interpreting the situation. A riser leak may have provided a neat explanation for the previous anomalous NPT readings and inability to bleed the pressure off the drill pipe. .	The well site leader and tool pusher mentally simulate two options for the falling volume (riser leak or a well leak) and decide to do another NPT. They do not anticipate the effect of the spacer on the next test.	The group of crew and visitors may have *distracted* the crew's attention whilst interpreting the test readings and the riser leak. As the riser then remains static, it supports the *expectation* that the well is fine.
5.17pm **e** Mud offloading to the MN Damon Bankston ceased but it was unclear who was notified of this. The mud logger was not notified.	Drill crew are alerted that the unloading has been completed but the mud logger was not notified.	Update the current mental model that space has been made for the large amounts of returning mud from the displacement operation.	Anticipate where the returning mud will be routed to once the current pit is full.	Not *sharing information* between the drill crew and the mud logger which may have affected their ability to monitor the mud volumes.
~5.30pm **e** Second NPT. Able to bleed the drill pipe pressure down to 0psi with 15bbls bleed off but on closing it, it rose up to 773psi.	Able to bleed pressure down to 0psi on the DP with 15bbls were bled off. Once the DP was closed back the pressure rose back up to 773psi.	Understanding that the DPP was bled down to 0psi and there was some bleed off. Without the expected amount of flow (3.5bbls) it would be difficult to interpret whether this was unacceptable and recognise the significance of the situation i.e. the test had failed. Unclear how the crew interpreted the instantaneous pressure build up on closing the DP, possibly their mental model still attributed the pressure as being related to the riser leak. It is likely that the current mental model was of the well being a closed system, making interpretation (of an open system) more difficult.	Do not anticipate that preparations are needed to calculate the acceptable amount of bleed off during the test (3.5bbls). It appears that the crew were unable to mentally simulate what could be causing the readings and the subsequent action of opening the kill line would suggest so.	The procedure for conducting the NPT was general and did not include specific instructions on how to interpret the results, making the interpretation more confusing (*work environment*). *Expectations* that the well was static in a closed system would likely have influenced the mental model.
~5.50pm **e** The well site leader ordered the crew to bleed off the DPP by opening the KL rather than the DP with the explanation of "let's open the kill line and see what happens". The pressure on the DP decreased to 0psi but the KL continued to flow and spurt up to 15bbls of seawater until it was closed (CCR, p.156). When it was closed the drill pipe pressure rose to 1400psi over the next 40 minutes	The DPP was bled down to 0psi but the KL continued to flow with up to 15bbls of seawater until closed in. The DPP increased to 1400psi in 40 min.	Deciding to open the KL to "see what happens" suggests that the well site leader was unsure about how to interpret the readings. Considering no expected bleed off calculations were made and that the previous bleed off of 15bbls was deemed acceptable, this was not interpreted as a fail. Unclear if the current mental model was updated with 15bbls coming out of the KL, what was replacing it or if the spacer was still above the BOP. The following meeting suggests that the increasing pressure was recognized as concern but not interpreted as the well flowing.	Do not anticipate that preparations are needed to calculate the acceptable amount of bleed off making interpretation more susceptible to error. Did not appear to mentally simulate the consequences of up to 15bbls of seawater coming out of the KL.	Lack of *experience* with such a large volume of heavy spacer may have influenced their mental model and mental simulations. Lack of *training, procedures or experience* in interpreting results for both the drill pipe and kill line
6.35pm **e** The crew gathered to discuss the anomalous readings with the two well site leaders, trainee well site leader, tool pusher and driller present.	1400psi on the DP which has increased over a 40 min period with two previous NPTs over the last 90 min. The experienced and trusted tool pusher, backed up by the driller, suggests an explanation for the anomalous build-up of DPP.	The tool pusher, backed up by the driller, interpret the 1400psi on the drill pipe as annular compressibility or the "bladder effect". If this were the case the pressure could be bled off, suggesting that the crew did not fully understand the explanation or integrate it into their mental model. That the well site leader (Vidrine) insists on another test on the kill	Anticipate that this situation may become a problem for completing the operation and installing the cement plug. Do not appear to have mentally simulated the effect of annular compressibility on the current mental model or what the expected readings would be.	*Expectation* that NPT would pass and that the cement job was already a success would have influenced the acceptance of the bladder effect. The majority of the crew members were trade men, without considerable *experience* with abstract engineering or physics concepts (CCR, p.162) making them more susceptible to accepting this interpretation. The

Table 3 (*continued*)

Event e negative pressure test	Information available (Level 1 SA)	Crew interpretation/ understanding (Level 2 SA)	Any predictions made? (Level 3 SA)	Influencing factors (PSFs)
		suggests that he did not fully accept the annular compressibility explanation.		tool pusher and driller were both considered experienced, trusted and well respected crew members, validating the *shared information*. Group think & Confirmation bias.
~6.45pm e Prepared for the second attempt at NPT by opening the KL and bleeding down to 0psi.	Able to bleed KLP to 0psi with 15bbls of continual bleed off and DPP 1400psi.	Without expected bleed off volumes and 15bbls previously being deemed acceptable, it is likely this was not interpreted as concerning. The 1400psi was now attributed to annular compressibility by at least the driller and tool pusher. However, the continual bleed off may have been interpreted as anomalous so the crew decided to check that it contained seawater by pumping a small volume into a mini trip tank.	Do not appear to anticipate that preparatory calculations are needed for the expected amount of bleed off (3.5bbls), affecting subsequent interpretation. Mental simulations for what could be causing the continual bleed off may have prompted the checking of the kill line.	Normalisation of relatively large bleed off volumes.
7.15pm e After the KL was confirmed to contain seawater, it was re-opened. During that time the crew continued to discuss the readings with the tool pusher and driller apparently continuing to explain it through the "bladder effect" but all eventually agreed on the explanation (CCR, p.158).	The kill line contained seawater. On opening it, only a small amount flowed from the kill line (~0.2bbl) and then stopped, remaining at 0psi for 30 min. The 1400psi still present is still attributed to annular compressibility.	The kill line was confirmed to contain seawater, removing any doubt that it contained something else. With the annular compressibility to explain the 1400psi, the readings would have been interpreted as a pass for the negative pressure test.	Anticipation would now focus on completing the abandonment process rather than on alternative explanations for the readings.	A considerable amount of time spent discussing the problem suggests that the crew were seeking to ensure that a consensus was reached (*sharing information and awareness and group think*). The readings would have fit with their *expectation* that the NPT would pass, influencing and supporting their interpretation that the well was static.
8pm e The well site leaders conclude that the NPT is successful.	NPT is confirmed by the well site leaders to be successful.	Concluded that the well is static and the cement job is a success.	Preparation for the abandonment of the well.	Further confirms *expectations* that the cement job is a success and that the NPT would pass.

At the end of preparations for the NPT, the driller, Revette's, mental model would have presumably calculated the mud and spacer to be appropriately positioned above the BOP. It is now recognised that this was very unlikely (Chief Counsel's Report, 2011, p151; inaccurate mental model). Considering that the driller was unlikely to have had significant experience circulating such a large amount of spacer (see earlier), it is unclear whether he would have comprehended the considerable amount of time required to pump it into the correct position. Thus it is probable that the driller's mental model was inaccurate, likely affecting his subsequent interpretation of what was happening in the well in terms of the hydrostatic pressure in the upper parts of the well and BOP (level 2 SA), as well as anticipating the effect this may have on the subsequent negative pressure test.

4.1.2. First negative pressure test

Whilst preparing to conduct the first negative pressure test at 4.53pm, the Drill Pipe (DP) pressure was higher than expected. However, it does not appear that preparatory calculations for the acceptable pressure readings were required, thus there was no frame of reference for interpretation or recognition of the pressure reading as an anomaly (level 2 SA). Once opened, the DP and Kill Line (KL) pressure simultaneously increased and decreased respectively. Stored mental models and schemas held in long-term memory about the "U-tube effect" should have been activated with the knowledge that if the DP and KL contained the same fluid, the pressure should have matched (experience). This was recognised as an anomaly by Kaluza, the well site leader (Transocean Report, 2011, p.97; Chief Counsel's Report, 2011, p.153; level 1 & 2 SA) but it is likely that the drill crew's mental models were still inaccurate because of beliefs as to the position of the spacer. Thus, it is doubtful that they would have anticipated that this situation would reduce the reliability of the NPT or taken remedial action (level 3 SA and actions; Chief Counsel's Report, 2011, p.153).

4.1.2.1. First attempt to bleed pressure down.

On this first attempt to conduct the negative pressure test at 5pm, the crew were not able to bleed the drill pipe pressure off to the required level (see Fig. 2 for likely SA process for the first NPT).

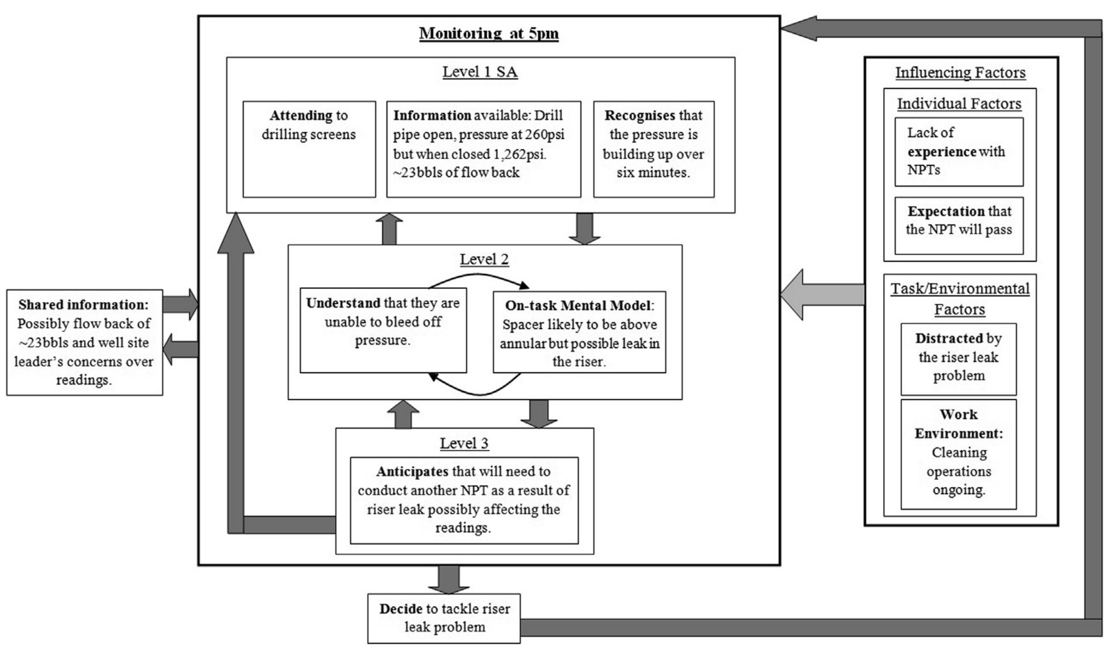

Fig. 2. Possible driller's SA for the first Negative Pressure Test at 5pm.

The approximation of flow from the well suggests that the crew were not accurately monitoring this flow (Chief Counsel's Report, 2011, p.153). Nor does it appear that the crew anticipated that they would need to make any preparatory calculations for the acceptable amount of flow from the well (level 3 SA). Unable to bleed the pressure down, the crew closed the valve on the DP suggesting that they recognised the changes in pressure and amount of bleed off (level 1 SA) but did not interpret them as a failed NPT (level 2 SA). It is possible that the crew interpreted the flow as being the result of downward pressure from the spacer rather than as an indicator of pressure increasing in the well. The expectation of the NPT passing and the subsequent distraction of the riser leak would have likely affected their understanding of the situation (level 2 SA).

At 5.10pm the crew recognised that the level of fluid in the riser was falling (level 1 SA) and their actions suggested that they were unable to effectively monitor the volume (Chief Counsel's Report, 2011, p.154). It is probable that they anticipated that another NPT would need to be conducted as a result of this falling fluid level (level 3 SA). The crew interpreted this as a riser leak which may have been affecting the previous pressure readings but it seems that this interpretation process was interrupted at 5.10pm by a personnel shift change and a group of visitors including BP and Transocean executives (distraction). The confusion at this time suggests that they were having difficulty interpreting the well state (level 2 SA & meta-cognition). Two conflicting explanations for the falling volume were reported: the riser leak or a well leak, and the crew decided to conduct another NPT although it appears that they did not anticipate the effect that these possibilities would have on the next test (level 3 SA).

4.1.2.2. Second attempt to bleed pressure down.

On the second set of bleed-offs, the crew were able to bleed the drill pipe pressure down appropriately but this rose back once the drill pipe was closed. Once more, no preparation for the acceptable amount of bleed off was calculated. That the crew started to immediately bleed off the pressure on the drill pipe (see below) suggests that they recognised the possible negative implications (level 2 SA) but likely had difficulty diagnosing the situation (level 2 SA). In addition, as mentioned previously, the procedure for conducting the NPT did not include specific instructions on what a failed test would look like (procedures/work environment). It is also possible that as the previous pressure on the drill pipe was attributed to the riser leak, this pressure increase would have been interpreted similarly. Consequently, it is unlikely that the crew would have correctly interpreted these readings as a failed NPT as a result of their misunderstanding of the well state, lack of acceptable flow calculations and insufficient procedures for interpreting the NPT.

4.1.2.3. Third attempt to bleed pressure down.

Kaluza, (the day shift BP well site leader) ordered the crew to bleed off the drill pipe pressure by opening the kill line rather than the drill pipe. Whilst this was outlined in the MMS approved procedure, the crew had not always followed these procedures so this order also suggested that he was unsure about how to interpret the situation (level 2 SA; meta-cognition) and that he and the crew were attempting to gather more information about the situation (level 1 SA). It is also possible that the crew were aware that they were having difficulties but did not wish to appear incompetent, so took no action to remedy this situation (Hopkins, 2012). The drill line and kill line flows which resulted from this action were, in the absence of any calculations of the acceptable amount of flow, coupled with the results of the previous NPT, being deemed acceptable (experience; normalisation of readings; level 2 SA error). As the crew shut the kill line whilst it was still flowing, this suggested that they were aware that this was an anomalous indicator but did still not interpret this as the well flowing (level 2 SA).

4.1.2.4. Bladder effect.

Having recognised that the increasing drill pipe pressure was concerning (Level 1 SA), the crew met at 6.35pm to discuss the anomalous readings (sharing information & awareness; level 2 SA). Ezell, the senior tool pusher, said later that the crew lacked training, procedures and experience for interpreting NPT results for both the drill pipe and kill line (R. Ezell Trial Proceeding Testimony, p.1679; p.1704; p.1800). At this meeting, Anderson, the tool pusher, interpreted the readings as being caused by heavy mud in the riser which exerted pressure on the rubber annular preventer, subsequently transferring pressure to the well bore and drill pipe, thus explaining each previous build-up of pressure, referred to as the “bladder effect” or annular compressibility (level 2 SA). The tool pusher, Anderson, apparently backed up by the driller, Revette, told the well site leaders, Kaluza and Vidrine that “*this happens all the time*” and they all eventually agreed to this explanation (Chief Counsel's Report, 2011, p.157).

If annular compressibility was the cause (which it was not, according to industry experts), the drill pipe pressure could have been bled off but as the crew did not take this action to gather further information (level 1 SA) it suggests that the crew did not fully comprehend or mentally simulate how the "bladder effect" concept worked in their on-task mental model (level 2 SA). The drill crew may also not have had the relevant technical knowledge and expertise to critically evaluate the complex situation (Chief Counsel's Report, 2011, p.162) or the assertiveness to challenge the Transocean tool pusher's concept of annular compressibility, for fear of 'losing face' (experience; social dynamics, Hopkins, 2012). In addition, the tool pusher and driller were both considered to be experienced, trusted and well respected crew members, their status validating the new information that they were telling the other drill crew members and the BP well site leaders (sharing information and awareness; R. Ezell trial proceeding transcript, p.1729; see Tharaldsen et al., 2010 for a discussion of trust in drilling). The expectation that the cement job was already a success and that the second NPT would pass would still have been present (confirmation bias). It is likely that these factors may have made the crew more susceptible to accepting the erroneous explanation as illustrated in Fig. 3 below.

4.1.3.Second negative pressure test

The well site leader, Vidrine, insisted that a second NPT be conducted but monitoring the kill line instead of the drill pipe as was outlined in the MMS approved procedure. Considering that the crew had not always strictly followed these guidelines, it is possibly that this was out of his concern for the anomalous readings, suggesting that Vidrine did not fully accept the annular compressibility explanation (level 2 SA; Chief Counsel's Report, 2011, p.157).

Without the previously calculated acceptable amount of volume and the knowledge of previous volume normalising the flow back volumes, the reading on the second NPT is likely to have been interpreted as acceptable (level 2 and 3 SA). The continued flow from the kill line was probably recognised as anomalous and disconcerting. Consequently, it is likely that the crew mentally simulated what was causing the continued flow - this may have prompted the action of checking it contained seawater and not spacer (level 3 SA; action; Transocean Investigation Report, p.99). After it was confirmed to contain seawater, the kill line was opened to continue with the NPT (level 1 SA). Evidence suggests that checking its contents further plugged the kill line with spacer, stopping any further substantial flow, and erroneously giving appropriate readings. The result of this 'successful' NPT would likely have confirmed the expectation that it would pass and that annular compressibility was the cause of the previous anomalous pressure (level 2 and expectation). The continued discussion of "annular compressibility" suggests that group think could have been impacting on the crew's decision making, seeking to ensure that a consensus was reached (sharing information and awareness; group think, Hopkins, 2012). At 8pm the well site leaders Kaluza and Vidrine concluded that the second negative pressure test was successful (level 2 SA).

The analysis stopped at this point. From 8pm onwards the driller, Revette, started to displace the heavier mud and spacer in the riser with sea water, re-routing the returning fluids to different pits to accommodate the large volume of fluid. This made it difficult to monitor the situation. There were a number of anomalous cues but the evidence suggests that these cues were missed.

At 9.20pm Anderson, the on-shift tool pusher, told Ezell, the senior tool pusher, during a phone call that the NPT went well and that "*Everything was fine*" (R. Ezell trial proceeding transcript, p.1682; Hearing before the Deepwater Horizon Joint Investigation Team, May 28, 2010, p.282). Between 9.40pm and 9.43pm mud started spewing out of the rotary table and the DPP increased from 338psi to 1200psi in 5 min. The AD, Curtis, calls the senior tool pusher, Ezell at 9.45pm to say that "the well has blown out … and [Anderson] is shutting it in now" (Chief Counsel's Report, 2011, p.181). At 9.49pm the gas from the blowout ignites and causes the first explosion.

4.1.4. Summary

The analysis of the Deepwater Horizon NPT with the DSA model emphasises the consequences of successively inaccurate SA on decision making and subsequent actions which, in this instance, resulted in the drill crew erroneously accepting that the well was stable despite signs to the contrary. The evidence in the reports suggests that the crew members recognised some of the available cues despite missing key information but did not appear to have understood their significance in the context of their mental model of the well state. Our analysis highlights how an inaccurate mental model and resulting expectations can impact on successive cycles of SA, influencing the interpretation of cues and how the situation is anticipated to develop. Distractions, inexperience and lack of procedures on how to interpret NPT readings, as well the possibility of fatigue and pressure to get the job done, would have likely influenced the crew's SA.

4.2. Preliminary evaluation of the DSA model

The evidence available from the investigation reports and court hearing testimony was examined for the drill crew's SA and then the extracted text items coded for the DSA components as a preliminary evaluation of the DSA model's suitability for the drilling domain.

Table 4 shows that all the cognitive components of the DSA model were identified from the sources comprising attention, gathering information, cue recognition, understanding, mental models and anticipation. The frequency data show that perceptual (level 1 SA) and comprehension components (level 2 SA) occurred more frequently than anticipation (level 3 SA) with understanding being coded most often. However, there is notable variation between the sources, in both length and frequency in which SA was coded, possibly as a consequence of the focus of the source and the topics covered (e.g. court hearing testimony discussed specific aspects of the event whereas the Chief Counsel's Report gave a full chronology of the event). The variability limits the conclusions that can be made regarding the validity of the DSA model.

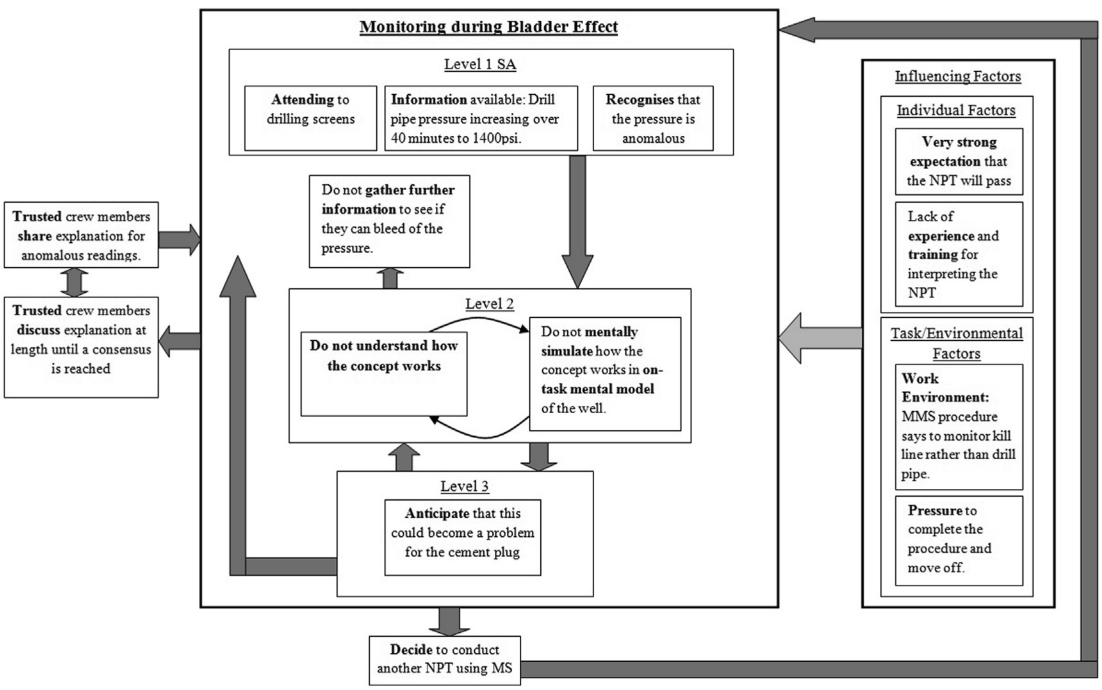

Fig. 3. Possible drill crew's SA for the bladder effect.

Table 5 shows the key influencing factors that were identified as potentially impacting on the drill crew's SA during the NPTs. Experience and work environment were coded most frequently, followed by expectations and distracters. Behaviours relating to sharing information and team work between the drill crew members were coded 62 times, most frequently in the R. Ezell BP trial proceeding testimony (14 times) and Chief Counsel's Report (2011; 8 times). Stress, workload, stored mental models and fatigue were coded infrequently, suggesting that they did not significantly impact on the drill crew's SA according to the available evidence. However, the variation in the sources and focus of investigation teams may have down played the impact that they may have had. Overall, influencing factors for SA are not significantly considered in the investigation into the event.

A drilling Subject Matter Expert (SME) verified the technical aspects, cognitive components and influencing factors that may have affected the drill crew's SA, supporting content validity of the analysis. The accident analysis provides a level of consistency with the previous interviews and observations (Roberts et al., 2015), supporting triangulation.

5. Discussion

By applying a situational awareness model (DSA) developed specifically for the drilling domain to the *Deepwater*

Horizon disaster data, we have illustrated how the crew's SA played a pivotal role in the disaster. The crew's erroneous SA led to them falsely interpret the NPT as successful, which in turn affected their subsequent decision to continue with the temporary abandonment procedure that caused the blowout. This analysis highlights the value of the DSA model in examining and analysing cognitive failures in drilling incidents. It therefore, emphasises the value of utilizing human factors investigation tools in the process industry, for example, HFIT (Gordon et al., 2005) which has been applied in a large petroleum company for gas platforms, floating production, storage and take-off units and gas processing plants (Antonovsky et al., 2014). The analysis provides preliminary validation for the utility of the DSA model for the drilling domain and as a consequence tentatively supports Endsley's (1995) model of SA. It also endorses Reader and O'Connor's (2014) and Hopkins' (2012) identification of cognitive issues associated with the event, such as inaccurate mental models and expectations which drove confirmation bias. This study builds upon their work by using a fine-grained event analysis to explain why the drill crew erroneously accepted that the well was stable. There is also the possibility that the DSA model could be refined and tailored for similar monitoring positions in the process industries (see below for recommendations).

Sneddon et al.'s (2006) analysis of SA in drilling accidents is supported by the results in Table 3 above. For example, they found level 1 SA errors associated with missing information (9.7%) and failures to monitor data (26.8%). We also identified errors of this nature during the *Deepwater Horizon* NPT. Sneddon et al.'s level 2 errors, relating to mental models (20%) were found to have a considerable impact on the interpretation of the NPT readings. Regarding the proportion of SA related problems identified during the *Deepwater Horizon* NPT, it appears that issues relating to missing information (level 1) and misunderstanding (level 2) occurred more frequently than anticipatory failures. Similar patterns of errors have also been found in other domains including aviation (Endsley and Jones, 1996) and maritime (Grech et al., 2002). The influencing factors identified in the NPT, such as workload, work environment, distracters and experience, also reflect Sneddon et al.'s interview study with drill crews on SA and the WSA rating tool (2006; 2013).

Table 4
Number of times the SA components and influencing factors were coded for each source and in total.

Source (no. Of pages SA was coded in)	Level 1 SA			Total level 1	Level 2 SA		Total level 2	Level 3 SA	Total no. of times SA coded
	Attention	Gathering Information	Cue Recognition		Understanding	Mental models		Anticipation (total level 3)	
Chief Counsel's Report (14pgs)	10	10	6	26	18	14	32	13	71
OLF Report (4pgs)	0	2	1	3	3	0	3	0	6
Transocean Report (14pgs)	6	8	4	18	15	5	20	5	43
Report to the President (8pgs)	6	1	1	8	12	2	14	2	24
BP Report (11pgs)	2	2	2	6	11	6	17	6	29
US Chemical Safety Board (12 pgs)	4	3	7	14	9	0	9	5	28
Deepwater Horizon Study Group Report (7 pgs)	6	7	8	21	12	4	16	8	45
R. Ezell BP Trial Testimony (80pgs)	5	6	3	14	12	2	14	5	33
J. Keith USCG Testimony (38pgs)	4	5	3	12	6	0	6	0	18
L. Lambert USCG Testimony (43pgs)	4	3	4	11	11	2	13	3	27
L. Linder USCG Testimony (36pgs)	3	3	0	6	7	2	9	5	20
Total (317pgs)	50	50	39	139	116	37	153	52	344

Table 5
Number of times the influencing factors were coded for each source and in total.

Source	Experience	Expectations	Stored mental Models	Stress	Distracters	Work environment	Workload	Fatigue	Total no. of times factors coded
Chief Counsel's Report	6	6	2	0	2	8	1	0	25
OLF Report	2	0	0	0	0	0	0	0	2
Transocean Report	2	0	2	0	0	4	0	0	8
Report to the President	1	1	0	0	1	4	0	0	7
BP Report	0	0	0	0	0	5	0	0	5
US Chemical Safety Board	2	2	1	0	1	2	0	0	8
Deepwater Horizon Study Group Report	3	3	0	0	1	1	0	0	8
R. Ezell BP Trial Testimony	19	3	0	0	4	5	0	4	35
J. Keith USCG Testimony	5	5	0	0	1	4	0	0	15
L. Lambert USCG Testimony	4	5	0	0	1	3	0	0	13
L. Linder USCG Testimony	5	4	0	0	0	3	0	0	12
Total	49	29	5	0	11	39	1	4	138

Fatigue, included in the WSA, was only mentioned briefly in the investigation reports, for instance, a number of the drill crew were close to the end of their rotas, making it more likely that they may have experienced fatigue (Burke et al., 2003).

The IOGP (2012) report on cognitive issues in the oil and gas industry emphasised the importance of maintaining an accurate mental model and explained the impact that inaccurate SA can have on process safety. Our analysis specifically identifies the SA components that led the drill crew to erroneously believe that the NPT had passed, including missing information, not recognising the significance of the available indicators and specifically examining the inaccuracies in their likely on-task mental model (e.g. whether the spacer was above the BOP). In addition, a number of individual and task/environmental factors that may have impacted on the drill crew's SA were identified, including lack of experience, expectations that the NPT was to be successful, distraction, lack of clear procedures and fatigue.

5.1. Limitations and future research

Whilst applying the DSA framework to the *Deepwater Horizon* disaster provides insight into why the crew interpreted the NPT as successful despite evidence to the contrary, there are a number of limitations. Firstly, as the main figures involved were killed in the blowout, the majority of the sources are secondary and consequently there is a risk of bias, in part due to their origins from the legal proceedings.

Where possible, firsthand accounts from transcripts were included to provide additional detail but these may also be distorted by biases, including hindsight bias (Dekker, 2007). It should also be acknowledged that the reports are a reflection of what was discussed during the investigation so it is possible that these may reflect the mental models and understanding of the lawyers and other individuals involved in the case, as much as those of the actual drill crew. Furthermore, limited attention was given to cognition and even less attention to influencing factors during the investigation. For example, none of the psychologists who had written expert witness reports were actually called to give evidence during the main trial.

Secondly, the SA framework was developed for an individual driller's SA but the event includes the whole drill crew. Whilst the processes and influencing factors involved overlap between individual SA and team SA (e.g. Endsley and Jones, 2011), it may be fruitful to further develop the framework for team SA (e.g. distributed SA; Stanton et al., 2009; Stanton et al., 2015). In addition, considering the involvement of executive management during their visit in the event, it could also be interesting to examine their awareness of the situation and how that contributed to the outcome.

The analysis preliminarily supports the suitability of the DSA model for the drilling domain using qualitative criteria (Miles et al., 2014). However, further evaluation will be required to test the validity of the components, as well as the processes i.e. that the components are present and in the order outlined in the model. Testing the prototype model against a body of accidents may also be valuable, such as using it to analyse a database of drilling incidents (e.g. Okoh and Haugen, 2013). We are now developing a performance measure of driller SA using an online simulated monitoring task which has the potential to quantitatively test the model's components and the relationships. A sequential analysis could then specifically test the predicted sequence of the cognitive components in the model, as has been recently reported for fire commanders SA and decision making (e.g. Cohen-Hatton et al., 2015).

5.2. Recommendations

Since *Deepwater Horizon* blowout, the oil and gas industry has recognised the value of human factors and of providing training in non-technical skills (NTS) such as SA (e.g. IOGP, 2012, 2014). Such efforts need to be encouraged, given that NTS have been found to play a critical role in maintaining safety and performance in other high risk occupations (Kanki et al., 2010; Yule et al., 2008; Fletcher et al., 2004; O'Connor et al., 2009). With the importance of monitoring in drilling, SA training of skills such as cue recognition, mental simulation, preparation for anticipated scenarios and coping with distracters may be worthwhile (e.g. Saus et al., 2006). The results of our analysis suggest a number of recommendations for maintaining accurate SA on the drill floor. Freer sharing of information between the client and operator would be valuable to reduce the risk that the drill crew do not have a full understanding of the situation from the outset, providing a solid foundation for decision making. The continual gathering of information, particularly during complex or ambiguous situations, should be encouraged to ensure that crew are not basing their understanding on assumptions. Well control training already emphasises taking the action to gather information on the situation by flow checking should the driller recognise a kick indicator (API, 2006; IADC, 2015). The power that expectations from hand-overs and meetings can have on subsequent SA should not be underestimated, with consideration to be given to how information is represented and framed during these periods (e.g. medical handovers, Manser et al., 2013; IOGP, 2014). Misinterpretation and anticipation failures were a source of possible error during the NPTs, suggesting that training and procedures should promote means of enhancing more accurate SA such as actively checking mental models (e.g. drawing a picture of the well), encouraging meta-awareness and seeking assistance when unclear (e.g. calling senior supervisors or the beach), as well as mental run-throughs for anticipated developments and required preparations. Considering work design recommendations for assisting SA would also be valuable such as ergonomic layout of information on display screens or software that assists cue recognition (e.g. Woodcock and Toy, 2011). The sterile cockpit concept, in which non-essential activities are dropped during critical periods, may also be helpful for reducing distracters and workload on the drill floor (Wiener, 1985; Broom et al., 2011).

Within the broader context of the process industries, it may be fruitful to consider specific SA training (e.g. nuclear power plant operators, Patrick et al., 2006; industrial operators, Nazir et al., 2015) or non-technical skills style training (e.g. Yim et al., 2013; O'Connor et al., 2008). There is the opportunity that the DSA model could be adapted for use in similar monitoring and intervention positions that require high levels of SA where operators continually attend to displays and the environment to build up an understanding of the situation and take decisions based on anticipated outcomes. For example, it could be tailored for other offshore positions (e.g. mud loggers or crane operators), nuclear power plant operators or petrochemical positions (e.g. refinery control panel operators). Consequently, the recommendations based on the *Deepwater Horizon* analysis may also be generalized for similar process industry positions, such as supporting the gathering and sharing of information between team members, actively checking mental models (e.g. confirming locations of volatile fluids or valve positions in a petrochemical plant) and encouraging seeking assistance when unsure (e.g. calling a supervisor when unsure about readings from a treatment unit in a refinery). Considering the impact of expectations from handovers on SA would also be valu- able (e.g. Carvalho et al., 2012).

6. Conclusion

This analysis of the situation awareness aspects of the *Deep water Horizon* NPTs provides (1) detailed insight into why the crew erroneously accepted that the NPT was successful and believed that the well was stable, influencing their decision to continue with the temporary abandonment procedure that culminated in the blowout. It also provides (2) preliminary validation for the utility of the prototype DSA model (Roberts et al., 2015) for the drilling domain. The analysis highlights how inaccuracies in SA, such as faulty mental models, can percolate through subsequent SA cycles, having considerable consequences for process safety. The crew appear to have misunderstood the situation with an expectation that the NPT would pass but lacking experience and procedures on how to interpret the anomalous NPT readings.

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Appendix A. Abbreviations and glossary

~ - Approximately.

Bbls - Barrels is the volume used to measure drilling fluids and hydrocarbons.

Bladder Effect - Heavy mud in the riser exerted pressure on the rubber annular preventer in the BOP, subsequently transferring pressure to the well bore and drill pipe, thus explaining each previous build-up of pressure. No industry experts have heard of or supported this explanation.

BOP - Blow-Out Preventer is a set of valves located at the top of the well that may be remotely closed to control formation fluids in the well. It can close around the drill string/pipe in the well bore to create a seal.

Boost Line - An auxiliary line which provides supplementary fluid supply from the surface and injects it into the riser to assist in the circulation of drill cuttings up the riser, when required.

Casing - A large diameter pipe lowered into an open well and cemented into place to stabilize the well and separate the formation from the well bore.

Cement - A material that is pumped into place to permanently seal annular spaces between casing and borehole walls. Various additives are used to control the density, setting time, strength and flow properties of the cement.

Choke line - A high pressure pipe coming from the BOP stack to the choke manifold on the rig that can be used to circulate drilling fluids during well control operations.

CCR - Chief Counsel's Report (2011)

DP - Drill Pipe is tubular steel conduit that connects the rig surface equipment with the bottom hole assembly and drill bit, that can be used to pump drilling fluid to and control the bottom hole assembly and drill bit. Multiple pieces can be joined together using threaded ends, called tool joints, to produce long drill strings.

DPP - Drill Pipe Pressure.

DSA - Driller Situation Awareness.

Float - A check valve that can be used to control the flow direction and/or position of drilling fluid or cement.

Kick - An influx of fluids into the well from the formation during drilling operations.

KL - Kill Line is a high pressure pipe coming from the BOP stack to the rig pumps that can be used to circulate drilling fluids during well control operations. It acts as a redundancy to the choke line.

KLP - Kill Line Pressure.

LCM - Lost Circulation Material is designed for plugging losses to the formation.

Mud - A generic term for drilling fluids including water, oil and synthetic based fluids.

NPT - Negative Pressure Test is used to test the integrity of the bottom hole cement job. Effectively, the downward hydrostatic pressure is removed allowing any formation pressure, should the cement job be ineffective, to enter the well bore manifesting itself as a pressure build up and flow from the well.

NTS - Non-Technical Skills are cognitive and social skills including leadership, communication, decision making, situation awareness and team work, as well as skills for coping with stress and fatigue.

OIM - Offshore Installation Manager.

PPG - Pounds per gallon is used to indicate the density of a drilling fluid.

Riser - A large diameter pipe used to connect sub-sea BOP stacks to floating rigs, transporting drilling fluids back to the rig surface.

Rotary Table - A revolving section of the drill floor that provides power to turn the drill string.

SA - Situation Awareness.

Spacer - Acts as a separating medium between drilling fluid and subsequent cement or sea water and can be used to disperse the drilling fluid from the well before starting a cement job.

Temporary Abandonment Procedure - A procedure used on a drilling rig to temporarily plug a well so that a production rig can complete it at a later date into a production well.

Tensioner - A device used to hold the riser in place between differential movements between the sea bed and floating.

Trip Tank - A mental tank with a small capacity that is used to monitor the well.

U-tube - This occurs when both legs of the U-tube - the drill pipe and the annulus up to the kill line - are opened and will balance out depending on the equal fluids which they contain.

WSA - Work Situation Awareness.

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