How cognitive task analysis (CTA) can improve learning from serious accidents

Ian Pemberton[1] & Domonic Mooney[2]

[1]Human Focus International Ltd, UK, [2]British Sugar, UK

SUMMARY

This study involved conducting a cognitive task analysis (CTA) based learning review of a serious accident that occurred at a British Sugar manufacturing plant in the UK. Exploration of the cognitive work, through the use of cognitive task analysis (CTA), delivered deeper understanding of the contributing factors to the accident, and helped to extend significantly the learning beyond that gained through the existing accident investigation. The results of the CTA interviews also provided content for scenario-based training, called decision-making exercises (DMX), which were shown to be effective in developing the tacit cognitive skills that contributed to this accident. This study provides convincing evidence that a CTA-based approach can help extend learning from serious accidents, both in terms of understanding contributory cognitive human factors, as well as providing rich content for cognitive tacit skills training for technical and non-technical skills routinely involved in serious accidents and fatalities (SIFs).

KEYWORDS

Practical application, cognitive task analysis, decision-making, expertise, manufacturing

Introduction

The rate of serious injuries and fatalities (SIFs) in workplaces, while on a downward trajectory over the last 40 years, has plateaued in recent years (HSE 2023). This plateau suggests that existing approaches to accident investigation, while valuable, might be missing learning opportunities. One evidence-based technique that might offer different insights and can complement existing approaches to workplace accident investigations is cognitive task analysis (CTA). CTA is a family of psychological research methods for uncovering and representing how people make decisions in real work environments, which are often messy and hard to uncover.

There are several foundational psychological models that underpin CTA. These include situational awareness (SA) (Endsley 1995), and recognition-primed decision-making (RPD) (Klein 1989). This paper reviews research that shows failures in SA are a prime contributory factor in the vast majority of SIFs (Flin 2014). It also reviews evidence showing how RPD has helped high-risk organizations achieve remarkable standards of safe performance, including in healthcare, emergency services, and the military. Of particular relevance to RPD is how CTA can be used to identify critical items of cognitive tacit knowledge held by experts, which, if identified, can be trained out to the rest of the workforce to rapidly enhance safety performance through a simulation-based training approach known as decision-making exercises (DMX). These nuggets of tacit skilled knowledge have been termed cognitive diamonds by CTA researchers and practitioners. In short, this study was an exercise in mining for cognitive diamonds in a sugar factory implicated in a SIF and testing how to rapidly implant these safety gems into the heads of the wider workforce.

Method

The study reviewed an existing accident investigation into a serious accident at a British sugar manufacturing plant in the UK. The study then moved into a CTA-based learning review stage. This involved conducting further CTA-based interviews, using an adapted critical decision method (CDM). CTA interviews were conducted with two workers directly involved in the accident, plus two interviews with resident experts who were taken through a simulation CDM interview to elicit their cognitive diamonds. The results of this CTA-based approach were compared with the existing accident investigation to identify differences in learning and insights.

The results of this CTA were then used to develop short interactive DMXs that were delivered via an online training platform. A small cohort of employees at the British Sugar site completed this training. Pre- and post-training benchmarks were taken to evaluate the results of the learning intervention.

Results

Results from the existing accident investigation versus the CTA learning review

A comparison of the existing accident investigation and the CTA-based learning review was conducted and is summarised here. Figure 1 shows a framework that was used to map learning from the accident. It compares two main elements:

1. **Workspace versus headspace.** The workspace encompasses external environmental factors, such as work systems, plant, and equipment. Headspace comprises internal cognitive factors.
2. **Failure versus success.** Failure is characterised by unintended negative work outcomes, including accidents, either due to equipment or work system design, or where people's actions failed to catch and manage risk effectively. Alternatively, success is defined by work outcomes being as intended or positive, either through good design of equipment and work systems or through resilient, skilful performance by people.

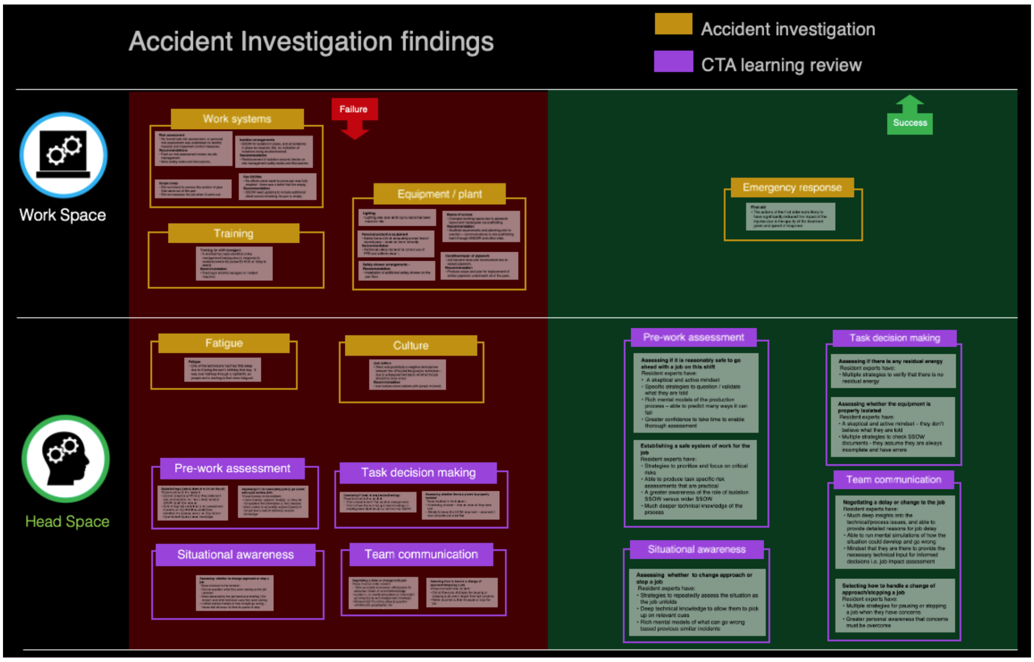

Figure 1: Framework for mapping learning from accidents

The results of the original accident investigation, along with the subsequent CTA-based learning review, were mapped onto this framework. Figure 1 provides a visual representation of this mapping exercise. It is striking that the results of these two exercises fall mainly into different quadrants of this framework. In general, the results of the accident investigation were almost exclusively in the top-left quadrant, i.e., the focus was on what went wrong in workspace factors. By comparison, the findings of the CTA learning review, as to be expected, fell in the headspace zone. However, it is significant that the CTA learning review findings covered both what went wrong (e.g., where people failed to notice warning signs or make good decisions) and successful performance (e.g., what resident experts would have done differently).

Results from the accident investigation

In the failure, workspace zone, the accident investigation found:

- **Work systems** – shortfalls in formal task risk assessment and personal risk assessments; isolation arrangements, scope creep in the task
- **Equipment/plant** – shortfalls in the condition of pipework; lighting; means of escape; emergency shower arrangements; personal protective equipment usage.
- **Training** – shortfalls in management response to the incident where police or HSE were likely to attend.

In the success, work space zone, the accident investigation found:

- **First aid** – the actions of the first aider were likely to have significantly reduced the impact of the injuries

In the failure, head space zone, the accident investigation found:

- **Fatigue**– one of the workers had little sleep and the accident occurred halfway through a nightshift
- **Culture** – there was potentially a negative atmosphere between two of the workers involved

Results from the CTA learning review

In the headspace, failure zone, the CTA learning review found those involved in the accident had:

- **Pre-work assessment –** shortfalls in technical knowledge; a trusting/passive mindset.
- **Task decision-making –** shortfalls in technical knowledge; a passive mindset.
- **Situational awareness –** limited mental models about how the task might go wrong.
- **Team communication –** shortfalls in team communication strategies to raise concerns.

In the headspace, success zone, the CTA learning review found the experts had:

- **Pre-work assessment –** deep technical knowledge of the process hazards; an actively sceptical mindset, e.g., they see their role as helping to make better decisions by identifying potential risks and suggesting improvements.
- **Task decision-making –** they had multiple strategies to assess residual energy in the plant pipework and for checking the validity of the isolation arrangements.
- **Situational awareness –** rich mental models that allowed them to run simulations of how things could unfold and potentially go wrong.
- **Team communication** – multiple strategies for pausing or stopping a job when they have concerns.

Comparison of the findings and approaches taken - accident investigation and CTA learning review

The analysis of the CTA interviews, when compared to the interviews from the original accident investigation, revealed the following differences:

1. **Interview length** – the CTA interviews were significantly longer than those from the original accident investigation. The average transcript length for the four participants interviewed in the original accident investigation was 587 words, versus 13,950 words in the CTA interviews. The CTA interviews were over 20 times longer. Figure 2 shows a graphical representation of these interview transcripts in respect to the number of A4 pages that they occupied.

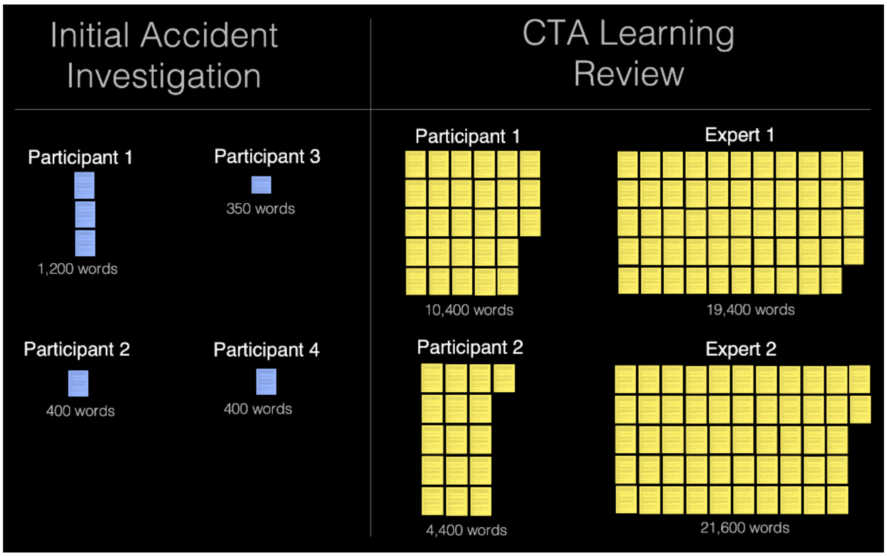

Figure 2: Graphical representation of the interview transcripts

2. Workspace versus headspace focus – the original accident investigation interviews were exclusively focused on what was happening in the workplace, i.e., a description of the events as they unfolded. Here is a selection of statements from the original accident investigation interviews that characterise this workplace focus:

*"**We checked** that the scaffold was tagged"*
*"At 2AM **I got a call** from the SPM to go and have a look at the job"*
*"**Tightening the union** was unsuccessful"*
*"We **tried to undo** these, but nothing moved"*

In contrast, the CTA interviews adopted a headspace focus – i.e., what was going on inside the heads of those involved. Following the CTA methodology, the questions were focused on asking the interviewees about their situational awareness, metacognition, and how they were improvising in the face of a complex set of goals, i.e., what they were sensing; what the sensory cues meant to them, and what they believed was about to happen. Here is a selection of statements from the CTA interviews that characterised this headspace focus:

*"So it was getting quite late on in the shift. Early in the morning, **when you're thinking am I going to be most alert**?*
*"**My plan was**, will do this quick uncoupling here."*

*“**I felt it was saefe.** As I say, I know XXX before he was sugar production manager …“*
*“**[My] assumption,** because we've been told this was empty, nothing should come back down this line.”*
*“**I did not believe** that that was my place [to question it]. I was still relatively new.”*

3. Significantly more tacit knowledge held by the experts compared to those involved in the accident – it was striking that the volume of cognitive diamonds (tacit knowledge AKA job smarts) held by the experts was significantly greater than that of the workers involved in the accident. Figure 3 shows photographs of the flipchart recording sheets that were used during the CTA interviews. Each post-it note that you can see can be thought of as a cognitive diamond at each step on the timeline of the accident. The point of showing this visual is not to provide detailed specifics, but rather to offer a visual overview of the difference in tacit knowledge. As you can see, the experts had a much greater range and depth of tacit knowledge with regards to this task.

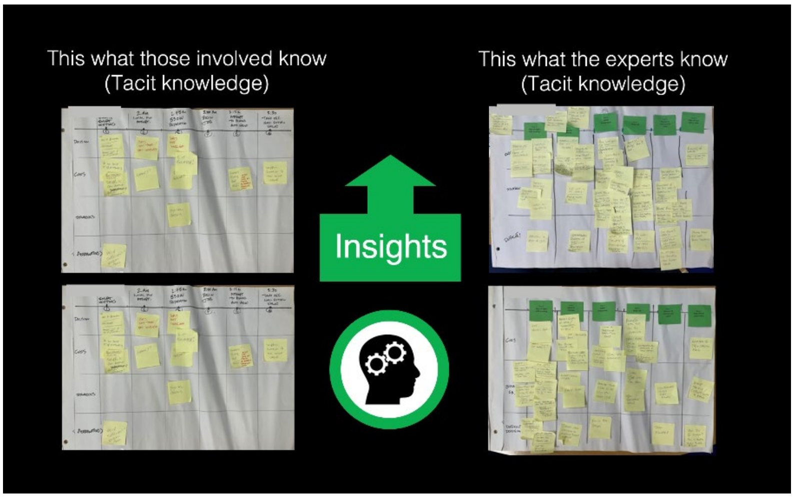

Figure 3: Interview recording boards

Training intervention developed from the CTA learning review

The analysis of the CTA interviews identified seven difficult decisions that were implicated in this accident. These difficult decisions were as follows:

1. Assessing if it is reasonably safe to proceed with this job on this shift.
2. Negotiating a job delay/change with the SPN [shift supervisor].
3. Establishing a safe system of work for this job.
4. Assessing whether the equipment is properly isolated.
5. Assessing if there is any residual energy in the line that’s about to be broken into.
6. Assessing whether to change approach, or stop the job.
7. Negotiating a change of approach to a job when circumstances change.

It is noteworthy that all seven of these difficult decisions, in addition to a good technical understanding of the processes, also require significant levels of non-technical skills (Flin et al. 2008, Flin et al. 2016) – in particular:

- **Situational awareness at all three levels** – being able to identify the correct cues in the given context of this task, understanding what they mean, and being able to project forward to make good decisions.

- **Communication** – being able to deal with team colleagues, particularly those in positions of higher authority. This is particularly important in difficult decisions 2 and 7.
- **Teamwork** – maintaining a good common ground understanding as this complicated job unfolded.
- **Decision-making and leadership** – being able to balance a complex set of commercial, technical, environmental, and safety requirements.

A decision requirements table was constructed, based on the CTA transcripts, for each difficult decision (adapted from Klein 2003). Figure 4 shows a sample page from one of these DRTs:

Decision 1: **Assessing if it is reasonably safe to go ahead with this job on this shift**

What makes this decision difficult?	Expert Cues	Expert Strategies	How your experts make this decision differently from those in the incident
• **Many competing demands** – i.e. safety, environmental, cost, reliability • **Key Information may not be immediately available**, e.g. Each job may require input from different people who may on different shift e.g. isolations, specialist support i.e. welders etc. • **Many process / technical complexities that need to be evaluated** i.e. the big picture • **Each job is context specific**, e.g. nuances that make standard work different	• **Have I done this job before?** i.e. Do I feel this is within my competency? Is this within my known limits? • **How much information have I been given?** i.e. instinctively know when it's insufficient • **What support functions are available on the shift?** Time of day plays a role e.g. middle of night – can the operations team cope with the impact I'm going to have on them? • **How will this impact on operations if done/not done?** • **Is there steam; hot liquids; chemicals; confined spaces; moving mechanical parts involved?** i.e. *'things that will really bite me or kill me' JM* • **What is the access like?** E.g. Ground level; up high; scaffold; other plant in the way? • **Have there been any previous incidents involved in this type of job?** i.e. your experts have a portfolio of these in their head for immediate comparison,	• **Go and physically look at the job** *"I go and look at the job and understand it. The little nuances of it" KF* • **Speak to other people who may have key information & need to be involved** *"Communication is all about bringing in the team so that they can help if things do go wrong" JM* • **Insist on taking whatever time they feel they need** to make assessment – will not be rushed • **Explain likely time range for job.** *"Important to be able to articulate how long the job is going to take. This is going to take three hours, but there's a chance that it might take eight hours but there's a one in 10 chance of this." JM*	• **Your experts have an active sceptical mindset** – i.e. they don't believe what they are told; they are curious and actively question. Those involved in the incident had a trusting / passive mindset, i.e. they did not question the information at their disposal. • **Your experts have a detailed / rich mental model of the production process and are able to rapidly evaluate the big picture accurately.** The key process hazard (condensation inside pan) was likely to have been identified and at an early stage. One of those involved lacked this technical understanding and was unable to identify the key hazard in this incident. The other had the process knowledge, but did not use it due to his passive / trusting mindset (see above)

Figure 4: Example Page from one of the DRTs which were constructed from the CTA interviews

Of particular relevance to the study was the extreme right column 'How your experts make this decision differently from those in the incident'. These observations were drawn from a comparison of what those involved in the accident were sensing, their understanding of these cues, and how they were making decisions, with the corresponding responses from the experts. This analysis revealed a large difference in situational awareness (SA), metacognition, and mental models between the experts and those involved in the accident.

Results gained from the enhanced CTA-based learning content

Figure 5 displays the results of the pre- and post-training scores for the three DMX simulation training scenarios. The results indicate a significant lack of tacit knowledge, implicated in this accident, within the training group. They also demonstrate that this tacit knowledge can be significantly improved after just one hour of online training. Furthermore, the results suggest that further improvement is required.

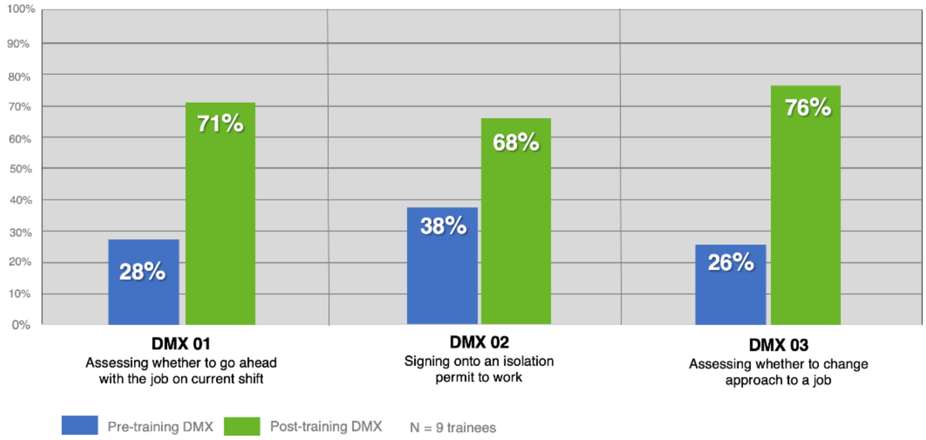

Figure 5 – Pre-and post-training scores in the three DMX scenario training courses

Discussion

Discussion of existing accident investigation

The results of the existing accident investigation were valuable. However, the findings were restricted to equipment and workplace organisation arrangements. There were no insights into the cognitive work involved in this task, and in particular, the expertise required to execute the maintenance task safely. The learnings from the CTA approach demonstrated significant shortfalls in the tacit knowledge of those involved in the accident when compared to resident experts. These tacit knowledge shortfalls were also found in the wider group of nine trainees who participated in the DMX exercise. Whilst these shortfalls in cognitive expertise and decision-making abilities were not the only contributory factors, they were significant. Therefore, while the existing accident investigation did deliver helpful learning, it is self-evident that it did not explore a significant contributory aspect of this accident – the cognitive work undertaken.

Discussion of the CTA learning review

The value of the CTA interviews with the accident participants was primarily to highlight how their cognitive performance differed from those of the resident experts. However, simply identifying shortfalls in the cognitive human performance of the accident participants does not provide the relevant insights into the positive tacit skills needed to improve human performance in this type of maintenance task, i.e., it doesn't mine for cognitive diamonds.

These CTA interviews did uncover a wide range of positive insights about the tacit skills that need to be developed, but this learning came entirely from the simulation interviews with the resident experts. This replicates the findings of other research, which found that interviews with resident experts, not directly involved in an accident, are instrumental in developing effective cognitive/intuition-based training interventions for safety-critical tasks (Staszewski et al. 2000). It is rare, if practically unheard of, for industrial accident investigations to routinely include cognitive-based interviews with experts who were not involved in the actual incident. This highlights another fundamental missed opportunity for improved learning during accident investigations. It is important to note that the positive tacit skills revealed through the CTA interviews with the experts included both technical and non-technical tacit skills.

Conclusions

The study has reached the following conclusions:

1. The existing accident investigation adopted an exclusive focus on workplace events that examined systems, equipment, and processes. Whilst this generated valuable learning, it did not explore the cognitive work aspects of the accident, which were subsequently found to have played a significant contributory role. This represents a blind spot and a large missed opportunity for learning following accidents – particularly in complex dynamic workplaces.
2. Exploration of the cognitive work, through the use of cognitive task analysis (CTA), delivered a deeper understanding of the contributing factors to the accident and helped to significantly extend the learning from this accident.
3. A large part of the learning from the CTA interviews was delivered via resident experts, who, not directly involved in the accident, were able to provide positive insights about safety-critical tacit cognitive skills through simple simulations.
4. The results of the CTA interviews provided content for intuitive skills training via context-specific simulation (DMXs), which were shown to be effective in developing the tacit cognitive skills that contributed to this accident. These tacit skills have broader applicability beyond the specifics of the accident studied.
5. The DMX training process provides a low-cost and practical way of accelerating the competency development of both technical and non-technical cognitive competencies.
6. The need for this type of CTA-based safety competency exploration and development, following serious accidents and fatalities, is a high and urgent priority for the following reasons:
   a. Cognitive tacit skills play a significant role in creating safe and reliable work systems. CTA, and associated DMX training, is one proven way of supporting the development of high-reliability work systems.
   b. Traditionally, it takes decades for workers to develop these cognitive skills through real-world trial and error experience and informal on-the-job training. However, increasingly the tenure of workers is falling. New ways of accelerating the development of safety-related tacit cognitive skills competency need to be explored, and CTA represents one evidence-based and practical option.
   c. As resident experts with decades-long tenure retire, there is a brain drain risk. Klein (1992) highlighted that a CTA approach can help to preserve corporate memory. It's vital that resident expert tacit knowledge is captured before they retire and recognised for what it is – an extremely valuable safety asset otherwise known as cognitive diamonds. CTA-based learning reviews are a practical way of counteracting this potential process of organisational amnesia.

References

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. Human factors, 37(1): 32-64

Flin, R., O'Conor, P., Crichton, M., (2008) Safety at the sharp end - A guide to non-technical skills. CRC Press, *Taylor and Francis*

Flin, R., Youngson, G., Yule, S., (2016) Enhancing surgical performance - A primer in non-technical skills. *CTC, Taylor and Francis*.

Flin, R. (2014) Non-technical skills: Enhancing safety in operating theatres (and drilling rigs). Journal Perioperative Practice, 24: 58-60

Health and Safety Executive (HSE) (2023). Work related fatal injuries in Great Britain 2022-23. Available on the HSE website: https://www.hse.gov.uk/statistics/fatals.htm.

Klein, G. A. (1989). Recognition–primed decisions. Advances in man machine systems research, edited by W.B. Rouse, 5: 47-92.

Klein, G. (1992). Using knowledge engineering to preserve corporate memory. *The psychology of expertise: cognitive research and empirical AI, 170-187. New York: Springer – Verlag*

Klein, G., Borders, J. (2003). The power of intuition. *Published by Doubleday, 36-83*

Staszewski, J.J., Davison, A. (2000) Mine detection training based on expert skill. *Detection and remediation technology for mines and mine like targets V. Proceedings of SPIE, 4038, 90-11*