

The vulnerability of rules in complex work environments: dynamism and uncertainty pose problems for cognition

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Many complex work environments rely heavily on cognitive operators using rules. Operators sometimes fail to implement rules, with catastrophic human, social and economic costs. Rule-based error is widely reported, yet the mechanisms of rule vulnerability have received less attention. This paper examines rule vulnerability in the complex setting of airline transport operations. We examined 'the stable approach criteria rule', which acts as a system defence during the approach to land. The study experimentally tested whether system state complexity influenced rule failure. The results showed increased uncertainty and dynamism led to increased likelihood of rule failure. There was also an interaction effect, indicating complexity from different sources can combine to further constrain rule-based response. We discuss the results in relation to recent aircraft accidents and suggest that 'rule-based error' could be progressed to embrace rule vulnerability, fragility and failure. This better reflects the influence that system behaviour and cognitive variety have on rule-based response.

Practitioner Summary: In this study we examined mechanisms of rule vulnerability in the complex setting of airline transport operations. The results suggest work scenarios featuring high uncertainty and dynamism constrain rule-based response, leading to rules becoming vulnerable, fragile or failing completely. This has significant implications for rule-intensive, safety critical work environments.

Keywords: rules; rule-based cognitive control; complexity; flight safety

1. Introduction

Rules are a fact of organisational life and they are abundant in many technology based, real-time systems, such as air traffic control, aircraft operation, power generation, computer security and nursing (Lorenz and Parasuraman, 2007; Moray, 2007; Pélegrin, 2013). Human activity in these systems is largely cognitive (Hollnagel and Woods, 2005) and it often falls to a cognitive operator to implement a 'ready-made' response to a system state – a rule. In safety-critical domains rules often

act as system defences. If a rule is vulnerable, then a work system may be more susceptible to adverse outcomes.

Rules are a key way in which organisations reduce variability and control outcomes (Katz and Kahn, 1978; Reason, 1997). Rules and procedures also perform a diverse and diffuse set of subtle functions, including specifying safe responses to system states, standardising team interaction, defining official task descriptions, soothing relationships with regulators and achieving political goals (see Bieder and Bourrier, 2013, for an excellent critical examination).

Rasmussen (1983) sought to provide a description of human performance in technology-based systems. He modelled human activity on three levels of cognitive control – skill, rule and knowledge-based. Rule-based behaviour involves cognitive operators retrieving and implementing ‘ready-made’ response to the environment. Rules are typically acquired from past experience, training, know-how or formulated in planning (Rasmussen, 1983). This is a relatively broad conception of rules which allows considerable variation in how formally they are specified, acquired and applied. In this research we are taking the more specific definition of: ‘if [condition x], then [behaviour y]’ (Moray, 2007; Reason, 1997). This closely matches structured rules that are formally specified (e.g. in an official task description) and part of a wider work routine. It nests in Rasmussen’s definition as it relates to a familiar work situation (the ‘if’ conditions) and a communicated instruction to control the outcome (the ‘behaviour’ output).

Rule-based cognitive control is often associated with decision making, even to the extent of attracting the label ‘rule-based decision making’ (e.g. Flin et al., 2008). Harris (2011) noted that a particular system condition may ‘map’ directly onto a stored rule, allowing the rule to function as a decision making artefact by specifying a response pathway. This form of decision making is common in medical and fault diagnosis, e.g. ‘if [indications a & b], then [problem is z]’ (Reason, 2008). This falls broadly within the Naturalistic Decision Making approach (Klein, 2008), which accommodates real-world constraints and the extensive use of rules and heuristics (Keller et al., 2010). By implication, rules may be very influential in some human decision making settings, although it may not always be obvious how and when a rule has been applied due to variations in formal specification.

Rule-based error

Operators sometimes fail to implement rules and Reason, Parker, and Lawton (1998) draw broad distinction between violations and mistakes, with violations being viewed as intentional. They also suggest certain types of rule-based error: apply a good rule at the wrong time, fail to apply a good rule and apply a bad rule. Humans may also circumvent rules for psychological reward – short cuts are common at the junction between the human and the rule. Arnstein (1997), for instance, suggests that senior anaesthetists are at greater risk of using short cuts than their junior colleagues. This is a form of self-organized error (Rasmussen, 1990) that emerges from local, optimized adaptation to work demands.

The idea of rule-based error (RBE) has seen widespread use across a variety of contexts. It is commonly invoked in anaesthesia (e.g. Arnstein, 1997), computer security (e.g. Kraemer and Carayon, 2007), nuclear engineering (e.g. Shen, Smidts, and Mosleh, 1997), nursing (Johnstone and

Kanitsaki, 2006; Henneman et al., 2010) and error taxonomies (e.g. Aronson, 2009; GEMS, Reason, 1990).

Complexity

Rules are a prominent feature in many complex work settings. These environments are capable of adopting a wide variety of configurations, thereby creating a large problem space. The attribute view of complexity (Walker et al., 2010) defines the ergonomic problem space as containing multiplicity (multiple interacting factors), dynamism (system state changes over time) and uncertainty (difficulty and vagueness in determining the final system state).

Pélegrin (2013) describes the airline transport cockpit as a complex and dynamic environment, and she charts the pervasive and ever-expanding nature of rules and proceduralization. The focus of this research was the stable approach criteria (SAC) rule in airline transport operations. The failure of this rule is the largest contributory factor in 'approach and landing' accidents in airline transport operations (Airbus, 2006). Its failure is an enduring topic in flight safety (e.g. Berry, 2008; Brady, 2013). The SAC rule specifies crew response for particular scenarios on the approach to land. The purpose of the rule is to ensure the aircraft is configured, with the right amount of energy, on a safe flight path, at a suitable distance from touchdown. It is implemented at certain 'gates', typically at 1000 feet in cloudy weather and 500 feet if the crew are visual with the runway. If the rule criteria are met, the crew can continue to land. If the criteria are not met, the crew are mandated to discontinue the approach. The criteria usually consist of several parameters, such as landing gear position, wing flap position, airspeed, vertical speed and proximity to planned flight path (Airbus, 2006). . It is formally specified (usually appearing in airline operating manuals) and takes the form '*if* [all stable criteria met] *then* [approach may continue]'. In February 2009 a Boeing 737-800 crashed on approach to Amsterdam Schiphol Airport, fatally injuring five passengers and four crew (Dutch Safety Board (DSB), 2010). During the final approach to land the crew twice failed to apply the SAC rule. The accident involved additional causal factors, but the crew neither discussed nor applied the rule at the airline's two 'gates', despite failing to achieve four of the specified eight rule criteria (e.g. the wing flaps were not set at the required position and the airspeed was beyond the rule tolerance, (DSB, 2010)). In RBE terminology, this is 'failure to apply a good rule'.

We selected to study the SAC rule as it is typical of rules in complex settings, requiring implementation amidst system dynamism and uncertainty. It acts as a system defence and provides a safe decision pathway for certain system states. In the context of this research, if the rule is not implemented at a point where it is acting as a system defence, the rule is deemed to have failed.

Our interest is in how system complexity could influence its use and failure. We believe system state complexity has been overlooked in studies of rule use and we suggest this could be an important aspect of rule vulnerability. This approach is distinct from that of pure 'rule-based error', as we were not simply investigating a dichotomous outcome (e.g. error yes/no, error recovery yes/no).

The aim of this study was to investigate the vulnerability of the stable approach criteria rule in the complex setting of airline transport operations. It was hypothesised that increased system state complexity (uncertainty and dynamism) would translate to increased likelihood of unintentional rule-based error.

2. Method

2.1 Design

An experimental, two-way, independent samples design was used. Four scenario vignettes were constructed based around the SAC rule. Finch (1987) notes that scenario vignettes capture multiple features of real-world events. A series of vignettes identifies which elements participants are responding to. This method was deemed particularly suitable because of its ability to describe highly realistic scenarios that would be very difficult to observe in a live work system.

The four scenarios were developed in consultation with management level pilots at the host airline. These pilots were familiar with system states associated with the failure of the SAC rule. The researchers used this knowledge to construct plausible scenario descriptions of varying complexity. Six operational pilots provided input in order to maximise the fidelity of the vignettes. This was accomplished through trials followed by open discussion. Particular care was taken to ensure scenarios closely matched real-world events, a key feature of the commonly used clinical vignette described by Hughes and Huby (2002).

The scenarios consisted of a description of an approach to land. Complexity was operationalised in the vignettes according to the attribute view (Walker et al., 2010). Uncertainty (difficulty and vagueness in determining the final system state) and dynamism (system state changes over time) were the independent variables. Each factor had two levels, high and low. The number of interrelated information cues (multiplicity) was held constant across conditions.

Uncertainty was operationalised through varying aircraft energy described in the vignette. A high aircraft energy state *reduces the certainty* of meeting future system criteria (a particular future system state), as the approach to land requires a series of

events to be coordinated that are contingent upon gradual energy reduction. Aircraft energy was adjusted by changing three approach parameters simultaneously (speed, altitude and vertical deviation from desired flightpath). This made the aircraft energy state unequivocal in each condition. So, the low energy condition translated to low uncertainty, and *vice versa*.

Dynamism was operationalised through varying the airborne wind reading described in the vignette (known as the Flight Management System (FMS) wind). A high wind reading (a form of environmental dynamism) results in greater number and magnitude of system state changes over time. Wind data are displayed to pilots on navigation instruments and pilots are familiar with the effects of wind on aircraft dynamics. So, the low wind reading condition translated to low system dynamism, and *vice versa*. An example scenario vignette (high dynamism/high uncertainty) can be found in the Appendix.

Participants responded to the vignette by answering the following question: 'What do you think the likelihood is of **this crew** unintentionally failing to apply the company stable approach rule at 500 feet?'

Participants used a 100mm, uni-polar visual analogue scale (VAS) [as described by Cowley and Youngblood (2009)] to indicate their answer. The VAS anchor statements were 'not at all likely' and 'extremely likely'. The dependent variable was 'judged likelihood of rule failure'.

2.2 Participants

Seventy five airline pilots took part in the study. The age range was 20 to 58 years. Mean age of the sample was 35.96 years (SD=8.92). The range of flying experience was 450 to 19000 hours. The mean flying experience was 4550 hours (SD=3344.73). Captains (N=31) had a mean age of 42.74 years (SD=8.31) and a mean flying experience of 7306.45 hours (SD=3573.97). First Officers (N=44) had a mean age of 31.18 years (SD=5.70) and a mean flying experience of 2607.95 hours (SD=1001.97). All participants held airline transport or commercial pilot's licences and were current in airline transport operations. They were all employed by the same airline, so used the same SAC rule.

Participation across conditions was as follows: low uncertainty/low dynamism N=20, low uncertainty/high dynamism N=17, high uncertainty/low dynamism N=20 and high uncertainty/high dynamism N=18.

2.3 Procedure

Prospective participants (normally in groups) were given a brief overview of the research, without explicit reference to 'stable approach criteria', to avoid priming. The research topic was described as 'approach procedures'. Anonymity and right to withdraw were emphasised. Verbal informed consent was required. Participants were randomly assigned a condition by being given an unmarked, sealed envelope containing written instructions, a practice scenario/VAS, an experimental scenario/VAS and a return envelope. Question papers were completed in classrooms or crew briefing facilities. Labelled fields (marked optional) were provided to record age, rank and flying experience. Respondents placed completed papers in the return envelope.

The authors observed the British Psychological Society Code of Human Research Ethics. They ensured that flight crews participating on operational flying days had completed their flight duty before taking part.

2.4 Analysis

Data from visual analogue scales (VAS) are known to violate assumptions of normal distribution (Dexter and Chestnut, 1995). It has been reported that parametric statistics (t, ANOVA), with no data transformation (e.g. to ranks), carry less risk of type I and type II errors when comparing VAS scores (Philip, 1990; Dexter and Chestnut, 1995). Statistical analysis used Factorial Independent Measures Analysis of Variance (ANOVA), carried out using PASW version 18 (IBM, Armonk, NY, USA). The critical α was set at 0.05 and the effect size was reported using partial eta squared (η^2_P).

3. Results

There was a Significant main effect for uncertainty, $F(1, 71) = 12.43, p < .01, \eta^2_P = 0.15$, with pilots reporting greater likelihood of rule failure in conditions of high uncertainty. There was a significant main effect for dynamism, $F(1, 71) = 7.10, p < .05, \eta^2_P = 0.09$, with pilots reporting a greater

likelihood of rule failure in conditions of high dynamism. A significant interaction effect was found between uncertainty and dynamism, $F(1, 71) = 4.51, p < 0.05, \eta^2_p = 0.16$. Figure 1 displays error bars for uncertainty and dynamism.

Insert Figure 1 here.

Figure 1. Mean judged likelihood of rule failure as a function of uncertainty and dynamism, showing 95% confidence interval error bars.

4. Discussion

Pilots reported a significantly increased likelihood of failing to apply the stable approach criteria (SAC) rule under conditions of high uncertainty. This is an important result, as many work systems can generate ambiguous, uncertain states. The SAC rule may be especially important in marginal, ambiguous conditions, where the rule is intended to be the arbiter between a safe and unsafe system state. This is illustrated by taking the reverse view: the rule is more reliable under conditions of certainty, or relative ease in determining the final system state. This would predict that approach scenarios that fall clearly and emphatically into a particular category (high certainty), would foster less rule-based error. This is problematic. Examining two easily categorised approach scenarios illustrates this. An approach may be comfortably within the rule criteria and pose little cognitive demand on determining the final state. Alternatively, an approach may clearly be destined to exceed all criteria, again, posing little cognitive demand. Both of these scenarios offer the pilot transparency, ample notice of the end state and little difficulty selecting the appropriate response. The key point being, the rule is vulnerable under marginal conditions, not clearly defined states. This explanation is supported by data from the Turkish Airlines Boeing 737-800 crash (DSB, 2010), where the crew narrowly failed to achieve some rule criteria and furthermore, early in the approach it looked possible to achieve all or most criteria. This is typical of a marginal case that resulted in rule failure. As Hollnagel and Woods (2005) proposed that rule use is triggered by a defined system state, it is clear that rule and response may be vulnerable under marginal, borderline 'if' conditions. Complex work settings are prone to generate environments with uncertain, ambiguous categorical properties. Increased system state dynamism translated into significantly increased likelihood of failing to apply the SAC rule. This suggests that changing, developing and evolving circumstances place constraints upon the cognitive operator. Dynamism could be viewed as series of values that are moving. It would be the job of the cognitive operator to assimilate these moving values into a coherent system state on which to act. The importance of being able to emphatically categorize system states has already been discussed, but this may be further compromised by system dynamism. Of particular interest here is the fact that complex work environments may be very rarely at or near rest. In contrast, rules are static, abstract devices that would need to be compared, at a very fundamental level, with a static world. Consequently, dynamism and rules may be uneasy partners. Once again, this can be viewed from the reverse angle. Approach scenarios with relatively little change over time, even when sampled rarely, offer a degree of coherence. Highly dynamic states may be more demanding; sequential changes may need to be assimilated, or elements of the system state may need to be 'frozen' and defined, before rules can be used. In extreme cases, dynamic states may not stabilise (or apparently stabilise) in any particular state. This is a possible mechanism of rule vulnerability in dynamic environments. The Turkish Boeing 737-800 was in

abnormally dynamic conditions during its approach. The aircraft had not had the benefit of a long final approach and around both of Turkish Airlines' stable 'gates' the system state was changing at regular intervals (e.g. speed reductions, flap selections). The crew were occupied by tasks and state changes that, ideally, would have already been completed. It is plausible that fluid, dynamic events are not well suited to rules that require a 'snap shot' of the system. The significant interaction between dynamism and uncertainty indicates that complexity from different sources can combine to produce a cognitively demanding environment. In this case, high uncertainty combined with high dynamism presents significant vulnerability to the SAC rule. The present study manipulated complexity by varying aircraft energy and environmental dynamism. These are only two sources of complexity, amongst many possible sources (e.g. technical problem, conflicting information, system mis-behaviours, weather events). The Air France A330 crash in June 2009 (Bureau d'Enquêtes et d'Analyses, 2012) is an contemporary example of multiple sources of uncertainty and dynamism creating a very challenging environment. The results from this study clearly indicate that combinations of dynamism and uncertainty may place rule-based response in close proximity to failure (fragile) or lead to the rule failing completely (not implemented).

This is an important finding, given that complex systems can generate unusual, rare and confusing states (Rasmussen, 1983) that require humans to recall and implement rules and procedures. It also progresses the idea of 'rule-based error' to a richer, more informative stage: complexity as a key influence on rule *vulnerability*, *fragility* and *failure*. This widens the scope for understanding human response amidst real system behaviour. It factors in the potentially pivotal context in which the cognitive operator may find themselves. We put forward rule vulnerability (exposure to failure conditions), rule fragility (close proximity to failure conditions) and rule failure (not implemented) as useful conceptions to accommodate system and cognitive variety.

As discussed in the introduction, rules can be highly influential in decision making, as is the case for the SAC rule studied here. Thus, rule vulnerability may account for some decision errors in complex environments and it could be fruitful for safety investigators to examine the relationship between rules and decision output. It should be noted that the influence of a rule may be temporally remote from a decision (especially in dynamic settings) or even potentially harmful to a decision (by ambiguous, real-world cues not readily matching 'if' conditions, despite efforts by the cognitive operator). We view this research as an opportunity for system designers to examine scenarios that might render a rule-based response vulnerable or fragile. If this work was done in advance of a rule being designed into a system, mechanisms of rule failure could be understood, and mitigations considered. We feel this is particularly important in work settings that rely on rules being implemented in potentially complex system configurations. This, perhaps, would start to redress the balance from Péglerin's (2013) 'never-ending' expansion of rules, to more astute 'rule and response designing'. This also opens up the possibility of educating system operators in the characteristics of vulnerability and fragility. If these were recognised in real time, operators themselves could intervene, perhaps averting a complete rule failure (e.g. by recognising more complex examples of task execution).

This study supports the attribute view of complexity (Walker et al., 2010) as a useful concept in the realm of ergonomics and applied cognition. It has been able to capture deeper characteristics of the information environment that pose problems to human operators.

Several limitations should be acknowledged. Inherent in vignette studies is the problem of ecological validity. Although the authors are confident that the scenarios were realistic, it is troublesome to capture a system state and response via this method. Nevertheless, this is a reasonable starting point, given that probing rule failure in real environments would be very challenging. Other ways of operationalising complexity should be investigated. This study relied on pilots making speculative judgements with only limited variations of complexity. Capturing responses to complex scenarios warrants further attention in order to better discriminate between cognitive constraints. In addition to this, the use of only one rule was probed. Further work on different rules and settings is required prior to generalising beyond this context.

There are several avenues of future research. Firstly, the extent to which professionals rely on cases being stereotypical is worthy of investigation. Stereotypical presentation will provide the professional with certainty. Uncertain, borderline and poorly demarcated scenarios need to be better understood. Paradoxically, it is these marginal cases that may really need rule-based response. Linked to this, it would be fruitful to understand system dynamism as a cognitive constraint (e.g. the impact of unusual dynamism on human abilities to generate coherent system representations or 'snap shots'). It would appear that the number, magnitude and typicality of system state changes are key attributes of dynamic settings.

5. Conclusion

The aim of this study was to investigate the vulnerability of the stable approach criteria (SAC) rule in the complex setting of airline transport operations. The study has shown that when system states are marginal, poorly defined and uncertain, the SAC rule suffers increased likelihood of failure. Fluid, dynamic states, that may never stabilise into a coherent rule-compatible structure, also lead to an increased likelihood of rule failure. It is concerning that multiple sources of complexity can interact to further constraint rule-based response.

Many complex work settings rely heavily on rules to control outcomes. Rules vary in their formal specification, but ready-made, feed-forward human responses are ubiquitous in work systems. The rule scrutinised in this research is typical of a structured rule acting as a system defence. Complex system characteristics appear to pose problems for cognitive operators. We suggest expanding current conceptions of rule-based error to include rule vulnerability (exposure to failure conditions), fragility (close proximity to failure) and rule failure (rule not implemented). This accommodates the cognitive operator within the influential complex environment and adds fidelity to explanations of system behaviour. It ably embraces cognition and the systems approach to ergonomics, which we consider to be the two most important levels of explanation connected to this research topic.

Rule failures can have major human, social and economic impact. This research indicates uncertainty and dynamism pose problems for cognition. A finer understanding of deeper, complex system behaviour will benefit both individuals and organisations.

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Insert Appendix here.