The links between errors and error-producing-conditions in aircraft maintenance.

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SUMMARY

Six hundred and nineteen aircraft maintenance occurrences were analysed to determine the types of errors that preceded them, and the contributing factors that were associated with each error form. Ninety six percent of the occurrences resulted in whole or in part from human actions. The occurrences were analysed using a cognitive error model and a simple taxonomy of contributing factors. It became apparent that different cognitive error forms were associated with different contributing factors. Clearly, safety interventions must take into account the links between errors and their contexts.

INTRODUCTION

Since the 1970s, there has been a growing interest in the errors committed by operational personnel such as air traffic controllers, pilots and maintenance workers, and an accompanying realisation that errors, (or unsafe acts), can take a variety of forms, including slips, lapses, mistakes and rule violations (Reason, 1990).[1]

A theme common to most accident models is that errors occur in the context of contributing factors such as deficiencies in training, equipment, or procedures, and that in order to reduce the incidence of error, it is necessary to address these contributing factors (e.g. Raouf, 1998). Various taxonomies have been used to classify contributing factors for accident and incident investigation purposes. These range from the list of over 350 factors published by the International Civil Aviation Organisation (1993) to the relatively modest list of 37 generic situational and task factors proposed by Maurino, Reason, Johnstone and Lee (1995). Yet despite the widespread use of such taxonomies in investigations, they provide only rudimentary guidance to managers or safety officers faced with the need to develop interventions to target specific forms of error. Furthermore, although cognitive error models such as those of Reason (1990) and Rasmussen (1983) are now widely used in aviation safety contexts, there is a lack of information to indicate whether particular contributing factors are associated with an increased prevalence of particular errors, or whether contributing factors affect the incidence of all errors in equal measure. For example, it is unclear whether fatigue is more likely to increase the incidence of skill-based slips, or errors of problem solving; or whether time pressure is more likely to lead to memory lapses, or knowledge based errors. Such questions have more than merely academic importance. Clearly, in order to reduce the prevalence of specific errors it is necessary to understand the particular conditions which promote each form of error.

There is of course, a vast quantity of information in the psychological and ergonomics literature concerning factors affecting human performance. However, as Wickens (1992) notes, much of this

[1] Throughout this paper, the terms ‘unsafe act’ and ‘error’ have been used interchangeably.

research has involved a reaction time paradigm, and has not generally focused on the production of discrete errors. Hence, this information does not assist greatly in linking error forms to factors. A second potential source of information are the human reliability tables used in settings such as the nuclear power industry. Meister (1982), Swain and Guttman (1983), Williams (1988) and others have developed tables quantifying the extent to which particular contributing factors increase the prevalence of human error. For example, according to Williams, time shortage is associated with an eleven-fold increase in error prevalence, while operator inexperience increases error rates by a factor of three. Unfortunately, most of these lists were produced before cognitive models of error were available, and are generally based on the untested assumption that contributing factors increase the prevalence of all errors equally.

In summary, the extent to which particular forms of error are associated with specific contributing factors is unclear, not only in the context of maintenance, but indeed in other safety critical environments. The aim of the present study was to partly rectify this situation. This was achieved by analysing a database of aircraft maintenance occurrences using an approach which enabled errors to be examined within their ecological context, maintaining intact the links between errors and contributing factors.

METHOD

Safety occurrence questionnaire

A safety questionnaire was mailed to all Australian licensed aircraft maintenance engineers. As well as collecting information on a range of safety-related issues, the survey provided respondents with the opportunity to report a safety occurrence. Those respondents who reported an occurrence were prompted with a series of questions which asked them to describe the chain of events which led to the occurrence (including human actions), and indicate why they thought the occurrence had happened. Additional background information such as time of day was collected with the aid of multiple choice or restricted response questions.

Data analysis

The outcome of each occurrence was coded using a descriptive taxonomy based on the Maintenance Error Decision Aid (MEDA) system developed by Boeing (Rankin and Allen, 1996). This taxonomy was used to describe the final result of the occurrence, such as ‘access panel not closed’ or ‘material left in aircraft’. The circumstances leading up to the outcome were then analysed using a technique developed by Williamson and Feyer (1990) combined with an unsafe act taxonomy based on that of Reason (1990). Where appropriate, contributing factors were linked with each occurrence. The factors used in this study were adapted from Williamson and Feyer (1990), (see appendix). Appropriate checks on the reliability of the coding system were carried out using a sample of dual coded occurrence reports. Acceptable levels of reliability were obtained.

Correspondence analysis

In order to examine relationships between unsafe acts and contributing factors, a cross-tabulation of unsafe acts by factors was analysed using correspondence analysis. Correspondence analysis is an exploratory procedure which converts complex data tables into two dimensional plots, making interpretation easier (Clausen, 1998). The correspondence analysis biplot expresses graphically the relative strength of the relationship between categorical variables. Categories which appear together have a stronger association than categories which appear apart in two-dimensional space.

RESULTS

One thousand three hundred and fifty nine questionnaires were returned, representing a response rate of approximately 29.5%. Most respondents did not describe an occurrence in their completed questionnaire, however, 619 useable occurrence reports were received.

Outcome of occurrence

The outcomes of the reported occurrences are listed in table 1.

The most common occurrence outcome was a system operated unsafely during maintenance, for example where a mechanic in the cockpit activated one of the aircraft's hydraulic systems, unaware that another mechanic was currently working on the system elsewhere on the aircraft.

> An aircraft maintenance engineer gave a clearance to put air on a wing (activate a pneumatic system) when a component was not fully tightened. They didn't ask enough questions about other jobs/tasks being performed and didn't see the person who was fitting the component.

Table 1. Most common occurrence outcomes

Outcome	N	Percent *
System operated unsafely during mx	80	13
Incomplete installation	48	8
Person contacted hazard	45	7
Incorrect assembly or location	44	7
Towing event	44	7
Vehicle or equipment contacted aircraft	31	5
Material left in aircraft	27	4
Wrong equipment or part installed	23	4
Part not installed	22	4
Part damaged during repair	21	3
Panel or system not closed	21	3
Required service not performed	20	3
Equipment failure	15	2
Fault not found	15	2
Falls and trips	14	2
System not made safe before mx	12	2
System not reactivated/deactivated	10	2
Pin or tie left in place	9	1
Documentation error	9	1

Other	95	15

**Figures are rounded to nearest percent*

The next most frequent outcome was incomplete installation, typically involving fuel or oil plumbing connections being left ‘finger tight’ rather than properly secured.

> I was changing an electronic component on an aircraft. To remove the component, it was necessary to disconnect the pitot static lines from an unrelated system. After the electronic component was changed, it was checked and operated normally. However, I failed to re-connect the pitot static lines which were in a darkened area, and I dispatched the aircraft with no pitot static source to some instruments. The aircraft aborted takeoff and ground returned. Lines reconnected. Brain went on *walkabout* whilst performing a routine component change.

Unsafe acts

Unsafe acts were involved in 96% of occurrences. Twenty percent of occurrences involved memory lapses, as illustrated by the following example.

> Just prior to the departure of the aircraft, I remembered I had left a blanking plug within the engine inlet area. I advised the pilot that I needed to check that area again and retrieved the blank.

Seventeen percent of occurrences involved violations. Most violations appeared to be well-intended attempts to complete a task in the face of time pressures or other challenges.

> I was asked to certify for other personnel on the shift preceding and following who were not licensed on type. A Licensed Aircraft Maintenance Engineer (LAME) carried out an inspection behind a panel where horizontal stabiliser re-positioning was required to gain access to all screws for panel removal. He did not remove panel completely, just took out enough screws so he could lift panel edge up and carry out visual inspection with a torch, which meant that when inspection was completed he did not physically have to resecure panel in place. When I was asked to certify, I did not inspect the panel physically as all access stands had been removed and horizontal stabiliser had been re-positioned so that only the screws on the upper edge of the panel were visible, giving appearance from ground that panel was securely attached. During pre flight by another LAME and pilot, this was also not picked up and panel was missing on landing some time later.

Slips are errors which occur during the performance of simple, routine actions. They include cases where workers tripped, fumbled objects, or carried out an ‘automatic’ action in a familiar situation when they did not intend to perform the action in the manner they did. Thirteen percent of occurrences involved such errors.

> Without thinking, I moved to wipe oil with a rag. The rag was ingested in the engine intake causing FOD.

Rule-based errors can occur when a person is working in a familiar environment but where they fail to take into account circumstances which would have been apparent at the time. As a result, their actions result in unintended consequences. Ten percent of occurrences involved such errors. Rule based errors do not necessarily involve an intentional violation of procedures, but rather indicate that the person failed to apply unspoken rules of good practice to their work. Common forms of rule errors were untested assumptions, or failures to check systems before acting. For example, one of the most common rule based errors was activating hydraulics without first checking the position of cockpit controls.

A further 12% of occurrences involved knowledge-based errors, while 6% involved failures to perceive.

Three percent of the occurrences involved actions which were categorised as ‘no error’, as illustrated by the following example:

> An aircraft engineer was carrying out a service procedure on an aircraft in accordance with the maintenance manual. The manual however, contained an error, which had led the manufacturer to issue an alert bulletin to modify the service procedure, but the company had not issued this bulletin to its staff. As a result of the incorrect service procedure, an aircraft system failed to operate correctly during a functional test at the end of the maintenance procedure. The fault was rectified before the aircraft was returned to service.

Contributing factors

The most commonly coded contributing factor was pressure, followed by equipment, training, fatigue and coordination (see table 2).

Table 2. Contributing factors

Factor	Percent of occurrences involving factor*
Pressure	23.5
Equipment	14.4
Training	12.3
Fatigue	12.2
Coordination	12.2
Procedures	11.4
Supervision	10.4
Environment	5.4
Previous error	4.5

** Note that occurrences may have involved more than one factor, hence percentages sum to more than 100.*

Association between contributing factors and unsafe acts

Figure 1 presents the correspondence analysis plot expressing the relationships between unsafe acts and factors. It is immediately clear that factors are not equally associated with all forms of unsafe act. The following associations between unsafe acts and contributing factors emerged:

- The most common error type, memory lapse was closely associated with pressure and fatigue. The incidence of memory lapses in occurrences in which fatigue was involved was almost twice as great as its incidence in all occurrences.
- Rule-based errors were closely associated with procedural problems, coordination difficulties and previous errors.
- Knowledge-based errors showed a strong association with inadequate training, as would be expected by definition.
- Slips were most closely related to equipment deficiencies and fatigue.
- Violations were most closely associated with pressure and to a lesser extent with equipment deficiencies.

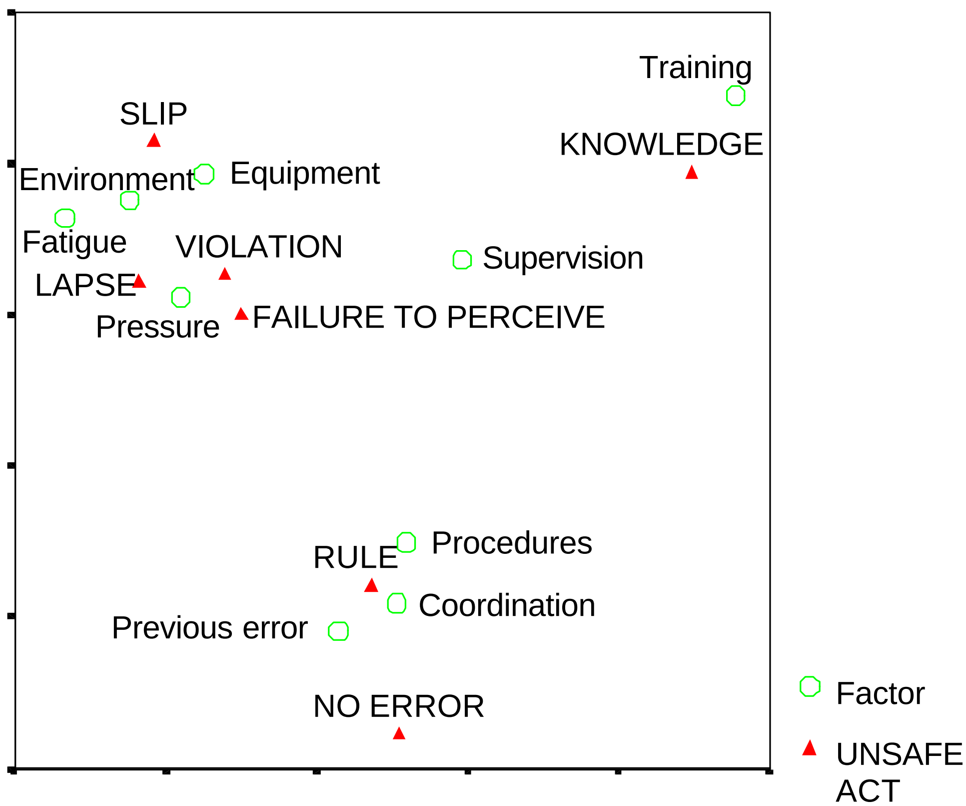

Figure 1. Unsafe acts by contributing factors.

DISCUSSION

The results have emphasised the primary place of human behaviour in the development of maintenance occurrences. Five types of unsafe act emerged as particularly important in the development of occurrences. These were memory lapses, violations, slips, knowledge-based errors and rule-based errors.

While expert opinion has long maintained that links exist between specific unsafe acts and particular contributing factors, this study has provided evidence from safety-related occurrences that contributing factors increase the incidence of particular unsafe acts, but do not necessarily result in an overall increase in all types of unsafe acts. So while rule-based errors were closely associated with procedural deficiencies, coordination problems and previous errors, lapses and violations were associated with pressure; slips were associated with equipment deficiencies and environmental factors; while knowledge-based errors were linked with deficiencies in training. Given that fatigue is a major issue of concern in industry, it is notable that the skill-based errors of memory lapse, failure to perceive, and slip were especially linked with fatigue. However other unsafe acts, particularly rule-based and knowledge-based errors were not associated with fatigue. This result lends support to the view that fatigue is most likely to interfere with a person's ability to carry out their intentions, but is less likely to degrade controlled processing such as that involved in rule-based and knowledge-based activities (e.g. de Vries-Griever and Meijman, 1987).

All field studies of safety occurrences suffer to a greater or lesser extent from the possibility that the data reflect biases. In the current study, judgements concerning factors were made on the basis of information provided by the reporter in response to prompt questions in the questionnaire. It is possible, and indeed likely, that the information gathered using this method has provided an imperfect picture of the context in which the unsafe acts occurred. Respondents may have been unaware of some of the circumstances surrounding the occurrence, or may have filtered or elaborated their responses on the basis of preconceived notions. Nevertheless, the data provided by the workers should not necessarily be seen as less accurate than that provided by expert accident investigators. It could be argued that the workers themselves are likely to have insights into the nature of their job, which would not be available from other sources.

It is hoped that the findings concerning unsafe acts and their context will be of use to maintenance managers who wish to target safety interventions on the basis of empirical data. Several possible interventions can be proposed:

Rule-based errors could be particularly reduced by improvements in coordination between workers, such as through maintenance team training (Taylor and Christensen 1998). Furthermore, the current results suggest that attention to the management of worker fatigue and production pressures would have benefits in reducing the incidence of memory lapses, the most common form of maintenance error. Similarly, violations could be addressed by better management of pressures and the rectification of equipment deficiencies. While it is highly unlikely that factors such as fatigue or pressure can be entirely eliminated from the workplace, it may nevertheless be appropriate to train workers in strategies to cope with production pressures and to ensure that rosters are designed in such a way that fatigue is kept within reasonable limits.

In conclusion, the current study has indicated that there are important relationships between error forms and the contexts within which they occur. Consequently it is clearly not sufficient to treat error producing conditions as though they were equally related to all error forms. Human behaviour in safety critical environments such as aircraft maintenance is in large measure a product of context, and the associations between errors and context must be taken into account, whether the aim is error reduction or error prediction.

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Appendix: Definitions of contributing factors	
Fatigue	The person was sleepy, generally related to a lack of adequate night time sleep and/or night shift work.
Pressure	Work was being performed under unusual time pressure or haste.
Coordination	Inadequate teamwork and communication between workers.
Training	Inadequate training of personnel.
Supervision	Factors relating to inadequate charge of workers.
Previous error	Incorrect performance of a task at an earlier time, where this error remained latent and was not recorded as an event in the occurrence sequence.
Procedures	Poorly designed, documented or non-existent procedures, or where a deviation from procedures was routinely accepted by management and/or personnel.
Equipment	Including poorly designed or maintained equipment or tools, or a lack of necessary equipment, including aircraft spare parts.
Environment	The physical environment in which the work was being performed, which was beyond the control of the worker. For example, darkness, glare, & noise.