Human Factor Determinants of Worker Safety and Work Quality Outcomes

Alan Hobbs
Australian Transport Safety Bureau, Australia

Ann Williamson
NSW Injury Risk Management Research Centre, Australia

The circumstances leading up to 619 safety occurrences that occurred during aircraft maintenance were examined. Ninety-six per cent of the occurrences were at least partly attributable to human actions and in most cases, these actions took the form of errors. The most frequent errors were memory lapses, rule violations and skill-based slips. Worker safety occurrences tended to be preceded by skill-based slips, whereas work quality occurrences tended to be preceded by memory lapses. It is apparent that safety interventions must take into account the associations between error forms and outcomes.

Accidents and the Human Factor

Human behaviour contributes to the majority of workplace accidents. Estimates of the involvement of human error in accidents range from 58% in medicine (Leape et al., 1991), 70% in aircraft accidents (Hawkins, 1993) to 80% in shipping accidents (Lucas, 1997). Aircraft maintenance is a safety-critical task where human errors can have serious consequences for the safety of maintenance workers, air passengers and crew. The maintenance work environment is unforgiving of error and includes hazards such as heights, powered machinery, confined spaces and dangerous chemicals.

As well as ensuring their own safety, aircraft maintainers must also sustain a high standard of work quality, yet the proportion of worldwide airline accidents attributed to maintenance error appears to be rising (Lowe, 1999). The following three examples, each from a different continent, illustrate the nature of the problem. In 1985, the world's worst single aircraft accident claimed the lives of 520 people when a Japanese operated Boeing 747 crashed into Mt. Osutaka. The aircraft had become uncontrollable after the rear pressure bulkhead failed in flight, destroying vital aircraft systems. The failure was the result of an improper repair (Job, 1996). In June 1990, a windscreen of a British Airways jet blew out as the aircraft was climbing to its cruising altitude, partially ejecting the pilot through the open window. It was determined that the windscreen had been installed by a shift maintenance manager using the wrong bolts (Air Accident Investigation Branch, 1992). In October 1996, a Boeing 757 crashed into the sea shortly after taking off from Lima, killing all 70 people on board. After takeoff, cockpit instruments had begun displaying erroneous airspeed and altitude information, eventually causing the pilots to lose control of the aircraft. While preparing to wash the airliner shortly before departure, ground personnel had placed masking tape over the sensor ports that provide information to the cockpit instruments. The tape was not removed after the aircraft had been washed, and was not noticed during pre-departure inspections (Walters & Sumwalt, 2000).

Work quality and worker safety are argued by many to be inter-related on the basis that work systems that produce good quality outputs will also be safe (Herrero et al., 2002). If so, managers in safety-critical industries such as aircraft maintenance could be assured that their efforts to manage worker safety will have payoffs in terms of work quality, and vice versa. While the human factors that relate to work safety have been studied extensively, those that relate to work quality have been the subject of significantly less attention.

Human Error and Safety

For much of the 20th century, psychology made little contribution to the understanding of the errors that occur in work and domestic settings. Spearman (1928) noted that "Psychologists positively decline to investigate error. They regard it as not being 'their job'" (p. 30). In the 1970s there was a renewal of interest in the errors of everyday life and industry. In Britain, Reason (1976, 1979) and Reason and Mycielska (1982) used diaries to collect examples of everyday "actions not as planned", mostly involving normal domestic activities such as dressing, cooking and washing. Reason (1976) noted that the errors of airline pilots sometimes resembled such everyday slips, and expressed the hope that investigations of domestic errors would help in the understanding of errors in less forgiving environments.

In Denmark, Rasmussen's explorations of errors in safety-critical industries led to the development of the skill-rule-knowledge (SRK) error framework. Skill-based errors typically involve absent-mindedness and may also be related to variability in the coordination of motor action, or failures to detect sensory input. Rule-based errors occur in familiar situations, often involving problems that call for explicit expertise. Rule-based errors include wrongly classified situations leading to the selection of a wrong rule, and incorrect recall of procedures. Errors at the knowledge-based level are a result of failed problem-solving and/or a lack of system knowledge (Rasmussen, 1980, 1982, 1983).

The SRK distinction has been further developed and popularised by Reason (1987) in his generic error modelling system (GEMS) which, like SRK, proposes three levels of human performance. The SRK framework also forms the basis of Reason's more recent unsafe act model, which

Address for correspondence: Alan Hobbs Ph.D., San Jose State University, NASA Ames Research Center, Mail Stop 262–4 Moffett Field, CA, 94035-1000, USA. Email: ahobbs@mail.arc.nasa.gov

includes rule violations as a distinct class of error (Reason, 1990). This model is now one of the most widely used error frameworks in the study of accidents (Lucas, 1997; Maurino, Reason, Johnston, & Lee, 1995; Shappell & Wiegmann, 1997).

In the field of safety, an extensive body of work has addressed the contextual circumstances related to errors and unsafe outcomes. A great variety of 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 SHEL model of Edwards and Hawkins (Hawkins, 1993), which encapsulates human factors in four broad categories: software, hardware, environment and "liveware", or interpersonal issues. Maurino, Reason, Johnstone and Lee (1995) propose a relatively modest list of 37 generic situational and task factors, including time shortage, lack of training, and inadequate tools and equipment. Williamson and Feyer (1990) list seven fundamental human factors that they applied in a study of fatal workplace accidents. It is not clear however, that such factor taxonomies are equally applicable to all types of occurrences. Some evidence suggests that there are classes of causal circumstances for different outcomes. For example, Salminen and Tallberg (1996) examined fatal and serious accidents in Finland and found that fatal accidents tended to be preceded by skill-based errors, whereas serious (but non-fatal) accidents were more likely to be preceded by rule-based errors. Despite the widespread use of error and factor taxonomies however, no information is currently available to indicate whether the behavioural precursors and contributing factors of quality incidents are the same or different to those associated with health and safety incidents.

In the present study a large database of aircraft maintenance occurrences was analysed to identify the forms of error that preceded them, and the contributing factors associated with the occurrence circumstances. The occurrences included incidents with safety and work quality outcomes, and provided an opportunity to compare the nature of human factors involvement in each type of outcome.

METHOD

Safety Occurrence Questionnaire

A safety questionnaire was mailed to approximately 4600 licensed aircraft maintenance engineers whose records were contained on a database held by Airservices Australia, as well as approximately 300 unlicensed mechanics employed by major airlines in Australia. In addition to questions dealing with working conditions and work practices, reported elsewhere (Hobbs & Williamson, 2000), respondents were given the opportunity to describe a critical incident. The critical incident technique, first described by Flanagan (1954) is now widely used in error research. The following statement was used to elicit incident reports:

> We are interested in your experience of safety incidents. Please tell us about a maintenance incident that involved you or someone else. A maintenance incident can be anything which could have prevented an aircraft from operating normally or could have put the safety of a worker at risk. Most incidents involve a chain of events. Start with the first thing that happened and then describe each of the things that happened next. Try to give as much detail as you can.

Reporters were required to indicate that they had either witnessed or participated in the events. They were then prompted with a series of open-ended questions about the circumstances of the occurrence and any human action, or inaction, that had featured in the events.

Data Analysis

The reported occurrences were analysed using the accident analysis approach developed by Williamson and Feyer (1990) in which the circumstances leading up to each occurrence are broken down into a sequence of precursor events. For the current purposes, the Williamson and Feyer technique was combined with an event taxonomy incorporating Reason's (1990) unsafe act model, but with the addition of the categories of "failure to perceive" and "behaviour, no error" (see Table 1). The outcome of each occurrence was categorised according to whether it presented a threat to work quality, worker health and safety, or both work quality and worker safety.

Where appropriate, contributing factors were linked with each occurrence. The factors used in this study were adapted from Williamson and Feyer (1990), with the addition of Fatigue, Pressure and Coordination. Contributing factors are defined in Table 2.

RESULTS

One thousand three hundred and fifty-nine questionnaires were returned, representing a response rate of approximately 28%. The returned surveys contained 619 useable occurrence reports, of which 96% were at least partly attributable to the actions of people. A total of 795 separate events were described in these reports.

Table 1
Event Taxonomy

Error or other event	Definition
Failure to perceive	The person failed to detect a sign that they were attempting to detect.
Memory lapse	The person omitted an action that they had intended to perform.
Slip	The performance of a familiar skill-based action at a time when this action was not intended, or the failure to carry out such an action correctly. This category included fumbles and trips.
Rule-based error	A failure to correctly invoke familiar rules or procedures, either written or based on experience when dealing with a routine problem, or when taking decisions in familiar situations.
Violation	An intentional deviation from procedures or good practice.
Knowledge-based error	An error in a situation that was unfamiliar or that presented new problems for the person, for which neither automatic mappings nor rules existed.
Behaviour, no error	The person adhered to correct procedures but their behaviour was nevertheless instrumental in leading to the occurrence.
Environment event	An event related to the natural environment, for example a weather event.
Hardware failure	A tool, equipment item, or component broke or malfunctioned.

Table 2
Definitions of Contributing Factors

Factor	Definition
Fatigue	The worker was mentally fatigued, generally related to a lack of adequate night-time sleep and/or night shift work.
Pressure	Work was being performed under unusual time pressure.
Coordination	Inadequate teamwork or communication between workers.
Training	Inadequate training of personnel.
Supervision	Inadequate charge of workers.
Previous-deviation	Incorrect performance of a task at an earlier time, where this deviation 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	Includes poorly designed or maintained equipment or tools, or a lack of necessary equipment, including aircraft spare parts.
Environment	Aspects of the physical environment in which the work was being performed, that were beyond the control of the worker. For example, darkness, heights and excessive noise.
Medical	The worker's performance was affected by a medical condition, or a sensory or physiological limitation.

Precursor Events

The most common precursor event (N = 143) was memory lapse, 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 (Anonymous survey report).

Violations were the next most common precursor event (N = 131). Most violations appeared to be well-intentioned attempts to complete a task in the face of time pressures or other challenges. The following incident was precipitated by a violation:

> We had some work to do in the forward cargo compartment. We wanted to get the maintenance done as quickly as possible, so an engine stand was used to access the cargo. The top of the stand is about 4 feet below the floor of the cargo, but was used because it was the only available stand in the area. A person fell out of the compartment onto the stand and then the ground after tripping while exiting the cargo compartment (Anonymous Survey report).

One hundred and one skill-based slips were identified, typically cases in which a person carried out an "automatic" action in a familiar situation:

> Without thinking, I moved to wipe oil with a rag. The rag was ingested in the engine intake causing FOD [Foreign Object Damage] (Anonymous Survey Report).

Ninety-seven knowledge-based errors were recorded. The following example illustrates a knowledge-based error related to a training deficiency:

> I wanted to turn the radio master on but could not find it, as the switches were poorly marked or unreadable. I was unfamiliar with the aircraft, so I asked ...[another worker]... and he pointed to a red rocker switch. I queried him and he said that must be it. I pushed the switch and the right engine turned over, with the propeller narrowly missing a tradesman who was inspecting the engine. There is no radio master in this aircraft. I immediately marked the "start" and some other switches and learned a valuable lesson. Poor training was a factor (Anonymous Survey Report).

Ninety rule-based errors were identified. For example, a worker wrongly assumed that it was safe to activate hydraulics

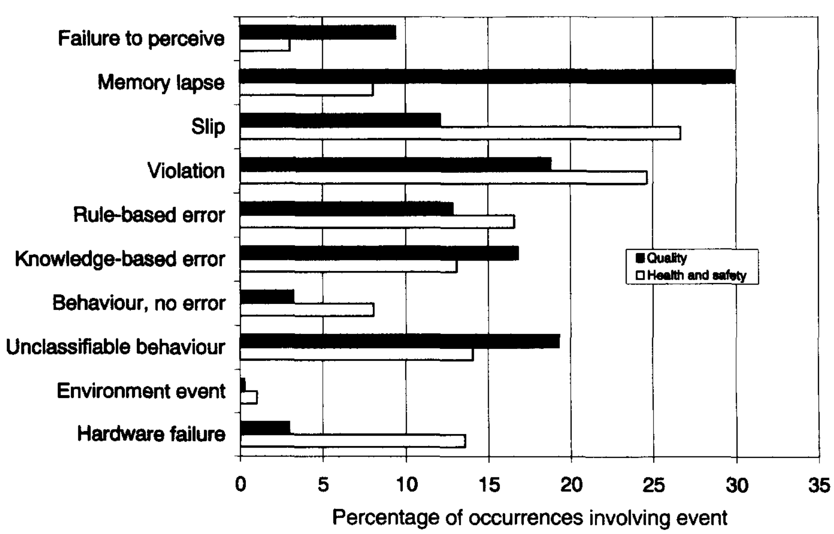

Figure 1
Precursor events for occurrences with worker health and safety implications (n = 199), and occurrences with work quality implications (n = 405).

without first checking the position of cockpit controls. Forty-six errors took the form of failures to perceive, typically cases in which a defect was missed during an inspection. Thirty actions were categorised as "behaviour no error", for example, where a maintainer accurately followed a service procedure, unaware that it contained a manufacturer's error. Fourteen per cent of events were human actions that could not be categorised further due to inadequate information. In addition to the behavioural events outlined above, 39 hardware failures and four environmental events were recorded.

Four hundred and five of the occurrences had implications for the quality of maintenance work, but did not involve a threat to the safety of maintenance workers. Examples of such outcomes were tools left in aircraft, wrong parts installed, and fuel or oil plumbing connections left "finger tight" rather than properly secured. An additional 199 occurrences resulted in real or potential threats to the health and safety of maintenance workers. Examples of such events were falls from ladders, electric shocks, or contact with hazardous equipment. Some health and safety incidents also had work quality implications, (e.g., where activating an aircraft system without prior warning could have damaged the aircraft and injured a worker); however, to avoid double counting, such cases were treated as health and safety occurrences rather than work quality occurrences.

As Figure 1 indicates, the distribution of precursor events was not the same across quality occurrences and worker health and safety occurrences. Notably, memory lapses were more strongly associated with quality outcomes than with health and safety outcomes $\chi^2(1) = 36.28$, $p < .001$. Slips, on the other hand, were more likely to have health and safety outcomes than quality outcomes $\chi^2(1) = 20.08$, $p < .001$. Hardware failures were also more closely associated with health and safety outcomes than quality outcomes $\chi^2(1) = 24.85$, $p < .001$. Violations were associated with both types of outcomes.

Contributing Factors

Compared to health and safety occurrences, quality occurrences were more likely to involve time pressure $\chi^2(1) = 7.92$, $p < .01$ and fatigue $\chi^2(1) = 8.61$, $p < .01$ (see Figure 2). Health and safety occurrences were more likely than quality occurrences to involve equipment deficiencies $\chi^2(1) = 20.81$, $p < .001$. The medical factor was used in only one per cent of cases overall, and has been excluded from further analysis. Note that in Figures 1 and 2, percentages do not sum to 100 as occurrences may have had more than one precursor event and contributing factor.

DISCUSSION

The current results have emphasised the primary place of human behaviour in the development of maintenance occurrences and the relatively small contribution made by hardware failures and environment events to such occurrences. Five types of error emerged as particularly important in the development of occurrences. In descending order of frequency, these were memory lapses, violations, slips, knowledge-based errors and rule-based errors.

The pattern of error associated with quality incidents was different to the pattern of error associated with health and safety incidents. Whereas quality incidents were most likely to follow a memory lapse, health and safety occurrences were more likely to be preceded by skill-based slips. The association between skill-based errors and worker safety occurrences is consistent with the findings of Williamson and Feyer (1990) and Salminen and Tallberg (1996) who in separate population studies of occupational accidents in Australia and Finland respectively, determined that skill-based errors were the most common behavioural precursors of accidents.

The current findings imply that in maintenance contexts at least, the errors that cause injury to personnel may require different interventions to the errors that affect the quality of the work they are performing. Efforts to reduce memory lapses, violations and knowledge-based errors may help to reduce quality incidents. Worker health and safety however, may be best served by attention to slips and violations and the circumstances that surround them, particularly safety equipment. The significance of violations as precursors of maintenance occurrences suggests that the prevalence of violations may be a valuable measure of an organisation's safety performance. The development of such an index could be a useful objective of future research.

In the current study, judgements concerning errors and factors were made on the basis of information provided by survey respondents in response to prompt questions. It is very likely that the information gathered has been affected by biases in reporting and recall. Respondents may have been unaware of some of the circumstances surrounding the occur-

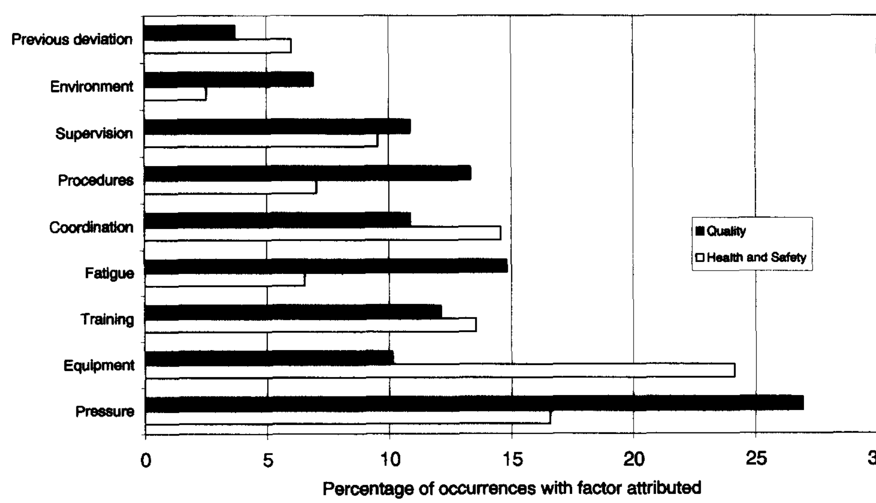

Figure 2
Contributing factors for occurrences with worker health and safety implications (n = 199), and occurrences with work quality implications (n = 405).

rence, or may have filtered or elaborated their responses on the basis of preconceived ideas. Nevertheless, despite their potential limitations, self-reports are one of the few ways of gaining insight into the nature of maintenance error, as few other sources of data exist.

In conclusion, this research has suggested that in aircraft maintenance, the causal pathways that lead to worker safety occurrences are different to those that lead to quality occurrences. Each type of outcome is likely to require a different set of interventions targeting the particular mix of errors and contributing factors.

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AUTHOR NOTE

Alan Hobbs is now at San Jose State University/NASA Ames Research Center, Moffett Field, California, USA

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