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Human Errors in Safety-Critical Workplaces: Innovation Based Errors

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Abstract

The concern of human errors occurring in safety-critical workplaces is often associated with damage to infrastructure, injuries or even death. However, the majority of humans are inherently driven to avoid errors, yet human errors continue to occur. This research study explored the interaction between humans performing high-consequence tasks and technology in the context of the aviation industry. The qualitative methodology that guided this research comprised of incident reports, observations and interviews with pilots and engineers who talked in depth about technology and relayed human error events in the context of a relatively small General Aviation (GA) private air charter business. The research reviews the conventional human error model of skill, knowledge and rule-based error (SKR) and uncovers a missing link in the SKR human error model, proposing an update to the model including an element that connects to the high-tech world of work that humans face in future innovative safety-critical workplaces.

Keywords:human error, mistake, safety-critical workplace, technology, innovation, human resource development

Introduction

Over 1500 years ago the Greek philosopher, Plutarch, cautioned Errare humanum est, sed perseverare diabolicum which coarsely translated means, ‘To err is human, but to persist in error (out of pride) is diabolical’ (Hoffmann & Beste, 2015). In fact, out of all the safety-critical industries, aviation activities regularly receive great public attention as these high-risk businesses often have an instant association to loss of human lives. Globally, the General Aviation (GA) sector’s fatal accident rates are often dwarfed by the news reports about the large-scale commercial passenger businesses with maximum capacities of over 800 humans. However, according to the latest figures from the Australian Transport Safety Bureau (ATSB) GA operations are approximately nine times more likely to have a critical incident and fifteen times more likely to experience a fatal accident than the large commercial airlines who principally operate the technologically up to date turbofan four engine aircraft and have access to modern safety systems (ATSB, 2019). The ATSB reported that in 2017 there were 21 fatalities from 93 accidents in GA operations in Australia. Akin to the ATSB is the independent United States government agency, National Transportation Safety Board (NTSB), responsible for accident investigations (NTSB, 2020). The NTSB also issued a similar statement in 2019 reflecting comparable numbers of fatalities in general aviation in the United States.

However, these fatalities were on a larger scale and showed an increase from 347 fatalities in 2017 to 393 fatalities in 2018 (NTSB, 2020). The NTSB Chairman Robert Sumwalt expressed his concern for GA in his annual report of glaring safety deficiencies by stating, "Aviators in general aviation communities need to renew their emphasis on building and sustaining a safety culture, and recipients of our safety recommendations in this area need to implement those life-saving recommendations." (NTSB, 2020). 4 So, the accident and fatal accident rates for GA in both Australia and the United States, reflects their riskier daily operating activity when likened to commercial air transport operations. Furthermore, while GA might have had an increase in reporting culture and general growth in small aircraft movements across these countries, a general consensus exists that operating a private air charter company nowadays is a very hazardous business (Fala & Marais, 2016; Karboviak, et al., 2018; Puranik, Jimenez & Mavris, 2017; Shappell, et al., 2017). Today, after multiple studies and documentation of new practices, human error is no longer seen as the leading trigger of an accident by many safety-critical organizations, but as a starting point to deeply investigate the root cause. This research delved into this perspective and then went further to reveal more information that leads to a better understanding of the interface of human intelligence and technology and how human error is perceived and managed in safety-critical organizations, more specifically in the aviation industry. To learn more about the interaction of humans with technology in safety critical industries like GA, and wondering if technology helps or hinders human error, this research study delved on the human side of this equation. By interacting with pilots and engineers who perform high consequence tasks in a GA safety-critical workplace, we observed, explored and examined the workplace, incident reports, and the stories as told by those pilots and engineers. The rich descriptions and in-depth conversations led to reviewing the types of human error as classified by previous literature, and resulted in a new proposed classification and a better understanding of how humans and a small and modern safety critical organization approaches human error in the 21st century. 5

Theoretical Framework

Safety-critical organizations

Safety-critical organizations are defined as those highly regulated businesses in which the well-being of humans is an overriding concern to the organization. If a disaster occurs then serious environmental destruction, severe damage to property, grave injury to humans or even loss of a significant number of lives can potentially occur (Wears, 2012). Safety-critical industries that are most commonly cited in the literature are aviation, healthcare, nuclear power plants, off-shore oil platforms, chemical plants, military, rail transport and construction (Edkins, 2002; Kletz, 2008; Lee & Harrison, 2000; Rothblum, 2000; Wears, 2012). Life-critical systems are distinct because the humans working within those systems are performing high consequence tasks and have a higher probability of making a human error that results in a system to malfunction (Reason, 1990; Wiegmann & Shappell, 2001a). *Classification of human error* After a major incident or accident occurs, a newsflash sometimes mentions that preliminary investigations are ruling out sabotage or terrorism and are pointing to human error. If it is an aircraft accident, the news report sometimes vaguely indicates the root cause of the accident by declaring whether it is a pilot or mechanical fault or sometimes both. The very nature of humans is to inquire and even demand to understand the reasons behind a disaster and this is generally expected in society, so lengthy investigations are launched. Yet, while the term human error may hold some weight to explain simple scenarios describing a human was somehow involved in an event and they have either not executed or planned an activity successfully, there has been little agreement on a clear-cut meaning of this expression over the last century (Fitts, 1951; Hollnagel, 2004; Illankoon & Tretten, 2019; Rasmussen, 1980, 1982, 1987). In Fitts and Jones's (1947) research on pilot error they 6 argued that human errors were simply an indication that there were other problems in the system and placed quotation marks around the word error. This denoted that human error was seen as an event that the human experienced with the machine, so it made more sense to recommend changes to the environment rather than to reprimand the pilot. Over seventy years later, Dekker (2017) followed Fitts and Jones's (1947) philosophy and placed quotation marks around the whole term 'human error' clearly representing that the label literally fails to justly explain the wider view of the human working in the multi-faceted context of a hazardous safety-critical workplace. Furthermore, what is seen as human error to one human may be defined as standard procedure to another who has an entirely different world view. As an example, in one study of two groups of humans counting errors of air traffic controllers (ATCs), the definitions of an error were vastly different (Hollnagel & Amalberti, 2001).

The ATCs were the subject matter experts, guided by the experience, insight and context in their field and overlooked some of the mistakes as genuine human errors because they regarded the ATCs as engaging and adapting to the challenges of their setting, tasks and real time situations (Dekker, 2017). The experts viewed the humans as doing the best they could under the circumstances, considering their tools, time and tasks. Over the last twenty years safety experts have banded together to agree that using the term human error to explain such complex systems like aircraft accidents is problematic (Dekker, 2016; Hollnagel & Amalberti, 2001; Rasmussen, 1990a, 1990b). To demonstrate a new image of human error, Hollnagel (1993) retitled it *performance variability* with an acknowledgement that adjustments in performance are required at both the individual and the organizational level. However, while this universal, widely-used term has been either mis-understood, disregard, or renamed, human error is most commonly approached by safety-critical industries in two different ways; as either an unintentional error or a deliberate violation (Embrey, 2005; Rasmussen, 1983; Reason, 1990, 2000; Wiegmann et al, 2005; Wiegmann & Shappell, 2001b). Nearly forty years ago, a taxonomy of human errors known as Skill, Knowledge, Rule (SKR) was offered as a valuable framework for identifying and classifying the different types of human errors (not violations) as shown in Figure 1 (Rasmussen, 1982, 1987; Rasmussen & Goodstein, 1985; Reason, 1990). Even though, this arrangement might be regarded as far too timeworn and unsophisticated to capture all the facets and complexities of how humans make mistakes, it is still a worthwhile instrument to categorize and then trace the basic origins of human error in a safety-critical organization. This SKR system of errors is divided into two distinctive failures of the human; execution and planning failures. If a human forgets to put something in the correct order or skips a step in the procedure, it is labelled a skill-based error because the human clearly has failed to execute or physically perform the critical task acceptably. The most common errors stem from skills-based errors which tend to occur when the human possesses the correct skills, is highly experienced and is very familiar with the routine and rules but unintentionally slips (Rasmussen, 1982; Salminen & Tallberg,1996). Missing a step, pressing the incorrect button, loosening something instead of tightening it or any action that is performed on autopilot by the human are representative of skills-based errors in aircraft maintenance or air charter safety-critical businesses.

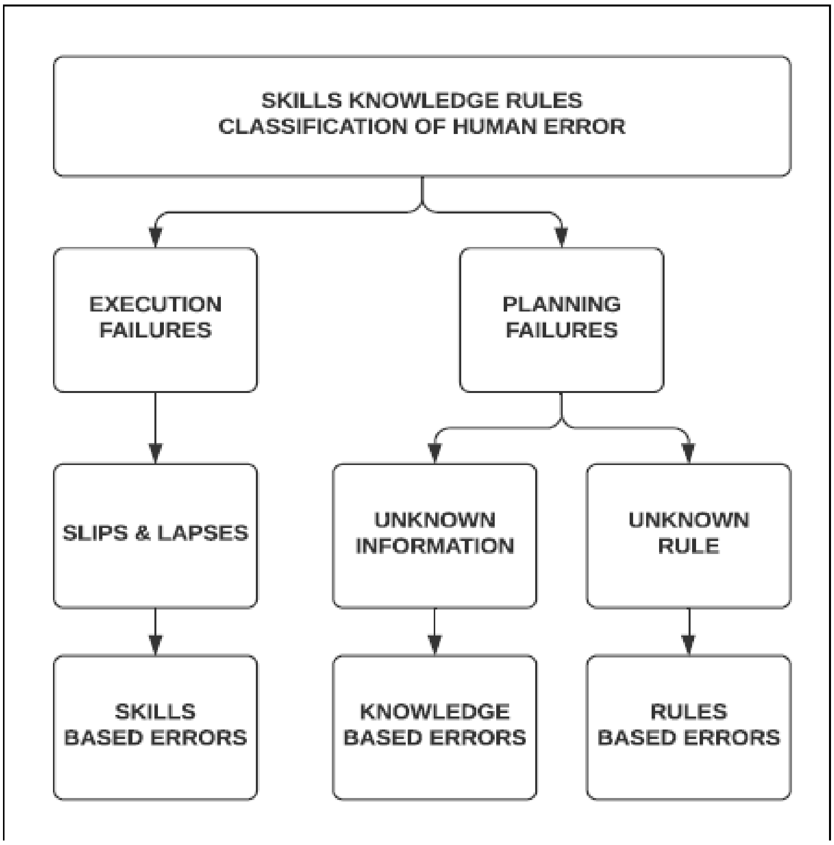

Figure 1. SKR Classification of Human Errors, adapted from "Human errors. A taxonomy for describing human malfunction in industrial installations," by J. Rasmussen, 1982, Journal of occupational accidents, 4(2-4), 311-333.

While slips are skill-based errors that occur when the human is being careless or not paying attention, lapses occur as a result of memory failure (Cak, Say & Misirlisoy, 2019; Rasmussen, 1982; Reason; 1990). Trials of the limits of humans memory span in the 1950's demonstrated that the longest list of items a human can recall is seven and this formed Miller's Law or the Magical Number Seven plus or minus two (Miller, 1994). Additionally, safety critical organizations have become well-known for the use of checklists to overcome the concern of memory failure and routinely use them to impart greater adeptness, constancy and safety in their workplaces as humans manage critical tasks under time pressure (Gawande, 2010). If a human is unaware of a rule associated with their critical task or misuses the rule by adopting an adverse norm from the workplace, then this is considered a rule-based error and is viewed as a human unsuccessfully planning to fail. Safety critical organizations realize that errors made due to inadequately trained humans who do not know the rules ormisuse an ineffective rule can be disastrous and seek out competent people through rigorous recruitment practices because those effective humans are the ones who, "... can create valuable results without excessively costly behavior…" (Gilbert, 1996, p. 17). Similarly, if a human enters a safety-critical workplace to perform a task with marginal or incomplete information about how to execute the critical task this too is viewed as a lack of training and a planning failure on the part of the human. *Human error models and organizational views* Over the last century safety-critical organizations have applied various human error models to both contain risk and explain human error in their businesses (Woods, Dekker, Cook, Johannesen & Sarter, 2010). Three accident models and one theory commonly referred to and have dominated safety-critical management meetings globally to address the issue of human error. These are (a) Domino Model, (b) Barrier (Swiss Cheese) Model, (c) Drift Model and (d) Systems Thinking. The Domino Model, originates from Heinrich's research nearly a century ago (1941) with his famous coining of the phrase unsafe acts. While the model offers some investigative advantages because it is easy to plot a narrative along a timeline, the idea of placing blame on individual humans who have tendencies to be accident prone, has been largely disregarded in many safety-critical organizations (Burnham, 2008). In direct comparison, the Barrier Model, sometimes known as the Swiss Cheese Model, identifies accidents as active errors committed by those humans working on high-consequence tasks (Hollnagel, 2016; Reason, 1997). However, this model goes further by concentrating on destabilized organizational conditions that conceal dormant errors within organizations. The Drift Model, also born in the 1970's, was really the first model to focus on explaining the incremental nature of drifting into accidents when humans start to make minor departures from operational procedure (Turner & Pidgeon, 1997; Vaughn, 1996, 1999;Weick, Sutcliffe, & Obstfeld, 2008). However, the model has received criticism as it is unreasonable to demand that humans remain constantly uneasy about impending disaster and also requires meticulous organizational supervision (Dekker, 2017; Hollnagel & Amalberti, 2001; Ludwig, 2018). Systems Theory or Systems Thinking is positioned separately from these three accident models as it does not rely on a linear cause-effect relationship to explain how accidents occur (Dekker, 2017). The main aim of System Theory is to "…explain things, natural or artificial, as that of systems and the interplay of their respective constituent parts" (Jacobs, 2014, p.22). In a safety system the machines and human resources are the inputs, how the organization uses those resources is the processes and the results are the outputs. If there is a fault feeding forward mechanism to support changes to the way humans and machines interact then the process is repeated.

Within their particular safety systems, some safety critical organizations make important decisions on how to distribute and coordinate work into different departments and support strategic directions based on systems theory that underlies most of Organization Development (OD) called the "open systems model." (Cummings & Worley, 2014). Even more significantly, with respect to Human Resource Development (HRD) safety critical organizations endeavor to connect the humans to their critical tasks. OD approaches for managing technological issues comprise OD activities involving employee involvement and work design and are called "technostructural interventions" (Cummings & Worley, 2014, p.154). When the development, design and operation of the whole system is closely examined by distinguishing the parts from the whole and then assembled together again in a novel way, then a clearer breakdown and analysis of how human error has occurred can emerge (Jacobs, 2019). Fundamentally this means Systems theory views safety-critical organizations not asstatic designs but as dynamic social processes with humans constantly acclimatizing to achieve objectives in a shifting socially organized system. There are two distinct approaches of studying human error in organizations; the person and the system approach (Dekker, 2017; Reason, 2016). The person approach observes the human performing a dangerous act or investigates a human error incident and immediately brands the human as forgetful, careless or inattentive or even negligent.

While this somewhat traditional perspective of safety maintains that problems are due solely to humans not following the rules, the system approach appreciates that humans are imperfect and flawed. Principally, the system approach recognizes that while the human's environment can be modified to build safeguards against catastrophic events, human error will still continue to occur (Rasmussen, 1997). Although there is a clear acknowledgement that the human condition of fallibility cannot be changed, the system approach makes a genuine effort to connect the human errors to systemic problems within the organization (Dekker, 2017; Von Thaden, Wiegmann & Shappell, 2006)

Supporters of the system approach often promote *just cultures,* which refers to a model of shared accountability around the complex systems that humans operate in, within a safety-critical organization (Dekker, 2017). Essentially this means, humans are responded to equitably, fairly and justly and the safety-critical organization consistently and reliably views the incident or accident as a learning opportunity and advocates determining more about how the organization operates, in order to have created the error in the first place (Dahlin, Chuang & Roulet, 2018; Dekker, 2016; Ludwig, 2018). While both the person and system approaches share parallel and respectable intentions to protect humans in the workplace, neither method has proven to be entirely successful, as human error remains the major cause of all workplace incidents (Dekker, 2014; Reason,

2017; Wiegmann & Shappell, 2017). Insufficient training and development within safety-critical organizations alongside human shortcomings of fatigue and complacency continues to trigger injury, illness or even death. So, with safety-critical organizations concerned with workplace productivity, financial costs and loss of time for both the organization and the human, some industries have started to show significant interest in new technological innovations to combat human error incidents (Gill & Shergill, 2004; Janic, 2000; He, Baxter, Xu, J., Zhou & Zhang, 2019; Taylor, Kazanzides, Fischer & Simaan, 2020) *Three Waves of Safety Training*

After the nuclear disasters at Three Mile Island (TMI) in 1979 and Chernobyl in 1986 operational safety training began to lead the agenda and attention shifted to addressing human errors in safety-critical organizations (Dekker, 2017, Edkins, 2002; Reason; 1997). The human factors training field emerged as an area of scientific knowledge that drew upon various disciplines such as ergonomics, physiology, psychology and engineering (Kelly & Efthymiou, 2019; Nagel, 1988). This first wave of safety training was to encourage the human to use personal protective equipment consistently and reliably, while the second wave was to introduce the concept of a safety culture. Nowadays a third wave of safety training involves computer aided smart technologies such as; virtual reality, augmented reality, wearable technologies, controlled lab tests, simulator-based training and video games to train humans who perform critical tasks and further raise safety awareness (Ceruti, Marzocca, Liverani & Bil, 2019; Chia, Lim, Sng, Hwang & Chia, 2019; De Crescenzio, et al, 2010; Kurd, Kelly & Austin, 2007; Niu, et al., 2019; Pereira, Moore, Gheisari & Esmaeili, 2019; Shmelova, Sikirda, Rizun, Lazorenko & Kharchenko, 2019).

However, technology experts agree that these need to be further trialed, substantiated and fully adopted across more safety-critical organizations (Bolton, et al., 2019; Dameff, Selzer, Fisher, Killeen & Tully, 2019; Gao, Gonzalez & Yiu, 2019; Kyriakidis, et al, 2019;Miller, Amin, Tu, Echenique & Winokur, 2019). Predominantly, in the aviation industry the number of accidents related to mechanical and technical failure have reduced considerably since the 1960's but human errors have declined at a considerably slower rate (Wiegmann & Shappell, 2017). It has become obvious that merely overcoming technical obstacles with technology is not effectual enough to mitigate human error. Also, it is predicted that a further wave of technology is going to eventuate sooner than anticipated and will occur in the form of a fifth Industrial Revolution and these rapid transformations will be a part of another social, political, cultural and economic upheaval (Brynjolfsson & McAfee, 2017; Daugherty & Wilson, 2018; Grace, Salvatier, Dafoe, Zhang & Evans, 2018; Schwab, 2016).

Future Workplaces for Humans

As automation begins to replace humans across the entire global economy, the question arises of whether those displaced workers find safe and rewarding jobs or will the revolution yield even greater inequality (Brynjolfsson & McAfee, 2015; Hauer, 2018; Vochozka, Kliestik, Kliestikova & Sion, 2018; World Economic Forum, 2016).

Essentially this means the Cyber-systems Revolution is more about humanity as a whole developing its own vision for the diffusion of the technologies which will empower fair and equitable social and economic development on a global scale. Researchers are beginning to comprehend the enormity of the phenomenon and the impact that this high-tech disruption might have on society as a whole (Daugherty & Wilson, 2018; Grosz & Stone, 2018; Helbing, et al., 2019; Jacobs, 2019; Keating & Nourbakhsh, 2018; Polson & Scott, 2018; Manyika, et al., 2013; Risse, 2019; Yu & Kohane, 2019). Nevertheless, the outcome for the human relies largely on the industry, region and occupation they currently survive in and on the response of the various organizational stakeholders who are in control of successfully managing the human's knowledge-work tasks(Jacobs, 2017). If humans are at risk of being less useful in the process of goods and services with the introduction of new technologies, there will inevitably be a political and governmental response to this social challenge of supporting an automated economy. Some researchers are offering the solution in the form of assuring humans are provided a universal basic income (UBI) but of course this would require a fundamental shift in how global economies are constructed (Santens, 2017; Sheahen, 2012; Susskind & Susskind, 2015). Ultimately, the successful integration of human intelligence and emerging technologies should mean that the diversity of humans is not compromised and collectively humans feel confident about the technological innovations and changes in their workplace (Auon, 2017; Bruun & Dukka, 2018; Brynjolfsson & McAfee, 2017). It is critical that marginalized social groups are not replaced in this process merely because they are unable to communicate about how these technological changes are affecting them (Dietvorst, Simmons & Massey, 2015; Friedman, 2017).

Other researchers, specifically in the medical field, warn that introducing a robust technological system that is unsupervised by humans might cause even more medical errors (Miller & Brown, 2018; Stelfox, Palmisani, Scurlock, Orav & Bates, 2006; Yu & Kohane, 2019). In fact, over fifty years ago researchers McCarthy and Hayes (1969) coined the phrase The Frame Problem and urged humans who have expert knowledge of specific tasks to closely monitor innovative technologies and to remain vigilant over workflows. Physicist, Stephen Hawking warned that some emerging technologies could end mankind and well-known entrepreneur Elon Musk openly cautions that AI is a genuine threat to human existence (Cellan-Jones, 2014). Undoubtedly, effective future technologies have the vast potential to completely transform how humans safely travel, work, communicate and essentially live their lives, but this comes with some level of threat to basic human rights and freedoms (Autor, 2015;

Russell, Dewey & Tegmark, 2015; Rasmussen, 1997). It is difficult to argue against the ordinary idea that underpins how emerging technologies should be developed for the common good and benefit of all humanity, nonetheless how it is regulated and controlled is a complex void in the research. While global multi-corporations and specific nations might advocate a safe code of conduct with reference to how they are developing and implementing technologies in their communities, there is an absence of an international code of ethics for specific new technologies like AI (Boddington, 2017, Greene, Hoffmann & Stark, 2019; Helbing et al., 2019).

Method

The purpose of this qualitative research was to study the different types of human errors that were occurring and the types of technologies that were being adopted to support humans while they performed critical tasks in a safety-critical workplace. We followed a generic qualitative study which was based on examining the social phenomenon of human error and we were interested in understanding the meanings humans have constructed in operating daily in an actual safety-critical setting. The goal was to produce a qualitative study that was thoroughly descriptive to deliver a genuine perspective of the humans involved by identifying recurrent patterns in the form of themes and categories of human error.

Research questions

The overarching research question was backed by sub-questions that steered the way to a deeper understanding of the research interest of human error. The principal overarching question that guided the inquiry was: *To what extent do technologies help or hinder humans who make human errors in safety-critical workplaces?*

The three sub-questions were:

1. What types of errors do humans make when performing high consequence tasks? 2. How does technology address those different types of errors? 3. How does the safety-critical organization address those different types of errors?

Research Site

The research site was a small-medium enterprise (SME) in Australia that operated with less than 50 employees such as; directors, aircraft maintenance engineers, pilots, flight and engineering instructors and administrative staff. It will be referred to as *Fly-Past* (pseudonym) in this paper. Two dynamic and diverse sections of the business became the focus that offered rich sources of data for human error, (a) an aviation maintenance repair and on the job training of aircraft maintenance engineers, and (b) an air charter and pilot flying school. This organization operated out of a secondary airport but was a busy, major GA epicenter for corporate aircraft, private charter, flying training and all kinds of maintenance training, supplies and requirements.

Research participants

The qualitative research methodology focused on in-depth narrations of the phenomenon of human error from four participants who were immersed in an aviation safety-critical context; two male aircraft maintenance engineers and two pilot instructors, one female and one male. They were appointed pseudonyms in the selection process; Jet and Baron were the engineers and Amelia and Charlie were the pilot instructors. All participants met the following selection criteria; (a) over 18 years old; (b) fluent in the English language, both spoken and written (c) had more than five years work experience; (d) routinely performed high consequence tasks in this safety-critical organization; (e) any gender; and (f) who had worked in the Aviation industry, for at least five continual years full-time.

While the aircraft maintenance engineers worked in the maintenance repair department through a standard working week from Monday to Friday, the flying school operated seven days a week, so the pilots worked in rolling shift patterns. All of the participants had substantial experience and knowledge of their roles and responsibilities.

Data collection strategies

The data collection strategies included the use of a field log, a private field journal, observation grids, and initial summaries of the data. The field log outlined the timing of the collection of the review of incident reports, observations and interviews that were prearranged to take place in that order. The private field journal recorded personal thoughts, feelings, impressions and questions throughout the course of data collection. The observation grids provided a framework that the research questions were directing the project and with definite guided notetaking throughout the observation phase. Initial summaries recorded all the major themes and patterns collected from the three sources of data; incident reports, observations and interviews. *Incident Reports* Full and complete access was acquired of all the most recent incident reports from 2019, captured in the secure online safety management system at the research site. Even though these incident reports were fragmented and trivial in quantity (33), the scope of their content allowed verification of specific information that participants referred to in the observations and discussed in the interviews.

Observations.

The observation sessions were used to relate naturally to all the participants and all efforts were focused on seeing how these humans interact with the general world of work in a GA safety-critical organization. Before and after each observation session field journal and observation grid notes were used to record the dates and periods of time spent observingparticipants.

Questions that resulted from the observations were examined and incorporated into the follow up interviews with the participants. *Interviews.* The third and final phase of the data collection included two separate forty-five-minute, face-to-face semi-structured interviews of the eligible and volunteer participants. They were conducted in person in a conference room, during a standard day shift. They were digitally recorded and took the 45-60 minutes as scheduled.

The goal of the first round of interviews was to hear about the participants involvements with human error and to learn more about the interaction of humans with technologies, and what impact that might have on human error.

The second interviews took place after each participant had received and reviewed a brief summary of what had been observed in the workplace and recorded in the first interviews. The goal of this second interview was to review the themes in the summary and provide an opportunity for the participants to clarify, modify, add more information or ask specific questions. It also gave a chance to ask additional questions about events that occurred on their shift during my observation phase and follow up on accounts in the first interviews. A semi-structured interview guide was used for each interview and modified in real time during the interviews. The discussion questions emerged from the themes from the incident reports, the observations and the natural flow of the dialogues. So, rather than a linear question and answer format strictly following a list of formalized questions, more of a dialogue was encouraged with the participants. Instead of answering direct questions participants were strongly encouraged to talk at length. Participants were guided to stay on the topic of human error and talk more about uncommon organizational incidents that might have occurred over their professional career.

All-encompassing questions were asked to gain an understanding of; the cause of the human error, a detailed description and outcome of the critical incidents, what actions were taken, how the participant felt and if they believed that any changes might be made in the future to mitigate the error. The style of questioning was not directed at yielding solutions for systemic problems in this particular safety-critical workplace but simply to listen to their perspective.

Findings

Largely, it was found that the air charter company responded effectively and efficiently to mitigate human error by using technologies such as; ATDs, warning systems in up-to-date cockpits and tracking applications for maintenance records. Also, other organizational arrangements and initiatives that they absorbed into their workplace culture, showed an obviously constructive and positive impact at the site. For example, the company reinforced a modern SMS and paired it with employing a qualified Safety and Compliance manager who was conversant in risk in safety-critical workplaces. Similarly, this safety-critical workplace managed to successfully mitigate risk through strongly supporting duplicate inspections. As an example, Jet described a failed duplicate inspection that required a third examination where a fault was finally detected in a critical flight control component. Jet claims that if the fragmented part had remained unnoticed and the engineers had both signed off on duplicate inspection as successfully completed work, it definitely would have caused the aircraft to crash. He labels the engineer who did not pick up the fault on the second inspection, "*lazy*" in the interview. Jet said: "*Lazy LAME came along and inspected the job for the duplicate… So, one wire was held in by a bolt the other by friction only. Like I said it was difficult to see and on top of everything a bad design but at the end of the day it was reassembled incorrectly by the first engineer. If they had flown with that it would have blown out and caused an accident. He only casually looked at the completed job. He had a general lookover not with the depth he should of. You gotta see everything that is done with your own eyes. Never assume. He did not detect it. It would have crashed if I had not checked it myself."*

The air charter company also followed an impressive ethos in their training departments by encouraging learning by observing, rather than learning by doing, especially when drilling pilots and engineers how to execute critical tasks. This style of observational learning includes watching experts, taking time to retain the information and then later on repeating and replicating the same actions that the student had observed. Amelia explained how too many pilot instructors relinquish the control of the aircraft to the student prematurely and do not offer enough time for the student to simply observe pilots flying. *"Honestly, students make a lot of critical mistakes. That is why I push observations over learning by doing. It is because the cockpit is noisy, uncomfortable and hot and bumpy. It is not a good learning environment. The student gets overloaded. The biggest key is to watch for them being overloaded. I don't talk about it while I am up there. I give them a brief five minutes while I demonstrate. I want to just demonstrate or show them. I need them to catch their breath. If they are becoming overloaded…. A lot of instructors try to give the controls too early.*

A second or third demonstration can be worth a lot of practices." So, with respect to the question of whether technology assisted humans in this safety-critical workplace, there was a clear indication that this organization did make respectable efforts at reducing the opportunities for human error with technology.

However, the reverse aspect of this question was to assess whether the presence of technology leaves the human less able to do their jobs safely and more prone to making errors. Technologies that automatically update pilots or engineers who then become over reliant on those systems was found to be a concern, particularly for the pilots. As pilot instructors, they agree with the literature that technologies sometimes fail, so training the human to draw on their own distinctively human skills, rules and knowledge to troubleshoot a critical issue is paramount in their training. To support this argument of the dangers of over-reliance on technology, the pilot instructor, Charlie explained an incident where he experienced dangerous weather conditions in flight and even though the autopilot is a technological system that is supposed to complement the abilities of the pilot, it is not something for the pilot to exclusively rely on. He says;

"The ATC was behind and it left me blind. Then the autopilot also failed me when I needed it most but it is not supposed to be there to fly the plane for me. There are limitations with the autopilot so therefore it couldn't sustain the aircraft in those kinds of lightning strikes. The autopilot failed. It momentarily lapsed us into an unusual attitude which required more skill than…oh well I guess you could say it required my full attention and all my skill at the time to bring my aircraft back into normal operations Sure, it is supposed to contain the fallout from the human mistakes we make. But we don't rely on it. I was stuck in a bad storm with people on board and just flew it myself. We need to know how to do it on our own."

So, for all the technological advancements in automation in aviation, it appears that the success of technologies such as these might be expressed as merely useful rather than attending to or addressing the real underlying issue of human error (Bainbridge, 1983). If the pilot or engineer is trusting the technology too heavily then this in itself is a human error and what is really needed is more training in specific skill sets that actually complement the technology. While the air charter business clearly demonstrated examples of growth and development in their safety management system in order to moderate error, there were some less anticipated qualities within the organization that exhibited an uncomfortable impression on the humans who performed the critical tasks. These cases were presented principally through the interviews with the humans where they revealed consistent remarks about the solitary nature of the job, snowballing job pressure and endless interruptions in some workflows. Baron the aircraft maintenance engineer clearly articulated the isolated feeling of a supervising licensed engineer by stating; "*Quite often as a supervising engineer you are left alone at the end of a day after a 11-hour shift or a late shift. This is where the trainees and apprentices leave but you are the one that has to sign off on the work. This is where you get tired and mistakes are made."* Both engineers consistently presented the topic of job stress and the tension of delivering a safe aircraft to the customer as a main source of human error and driver in making mistakes at work. There was a direct connection between being constantly subjectedto daily external pressures by the owners and operators of aircraft to produce the maintained aircraft. Within the aviation industry, there are clearly regulated work and resting periods for air traffic controllers and flight crew, yet aviation maintenance engineers do not appear to have the same strictly controlled break requirements within the General Aviation community (CASA, 2020). Baron states; *"Nobody is making money while aircraft are sitting on the ground. So, there is this constant underlying bottom line pressure*." With respect to pauses in workflows, during one observation in the maintenance hangar, I noted that the chief engineer was interrupted on fourteen different occasions. Jet describes these interruptions as expected and standard daily occurrences. He explained: *"Interruptions are just a part of my day. I have a lot of hats. I train, order parts, deal with customers, speak to reps, maintain the hangar. But what is the most important thing for me is I am careful when and what tasks I assign people and when I start a certain task. After lunch breaks is important. The timing is critical…"* A count of all the human errors found in both the incident reports and in theinterviews at the research site was linked to Rasmussen's SKR Human Error classification system and closely corresponded with his data (Rasmussen, 1987) which looked at skills, rules and knowledge-based errors. Illustrations of how well the data matched this governing study are shown in the statistics that there were more instances related to skill-based errors (55%) than there were rule-based errors (14%) and knowledge-based errors (17%) are shown in Figure 2 below.

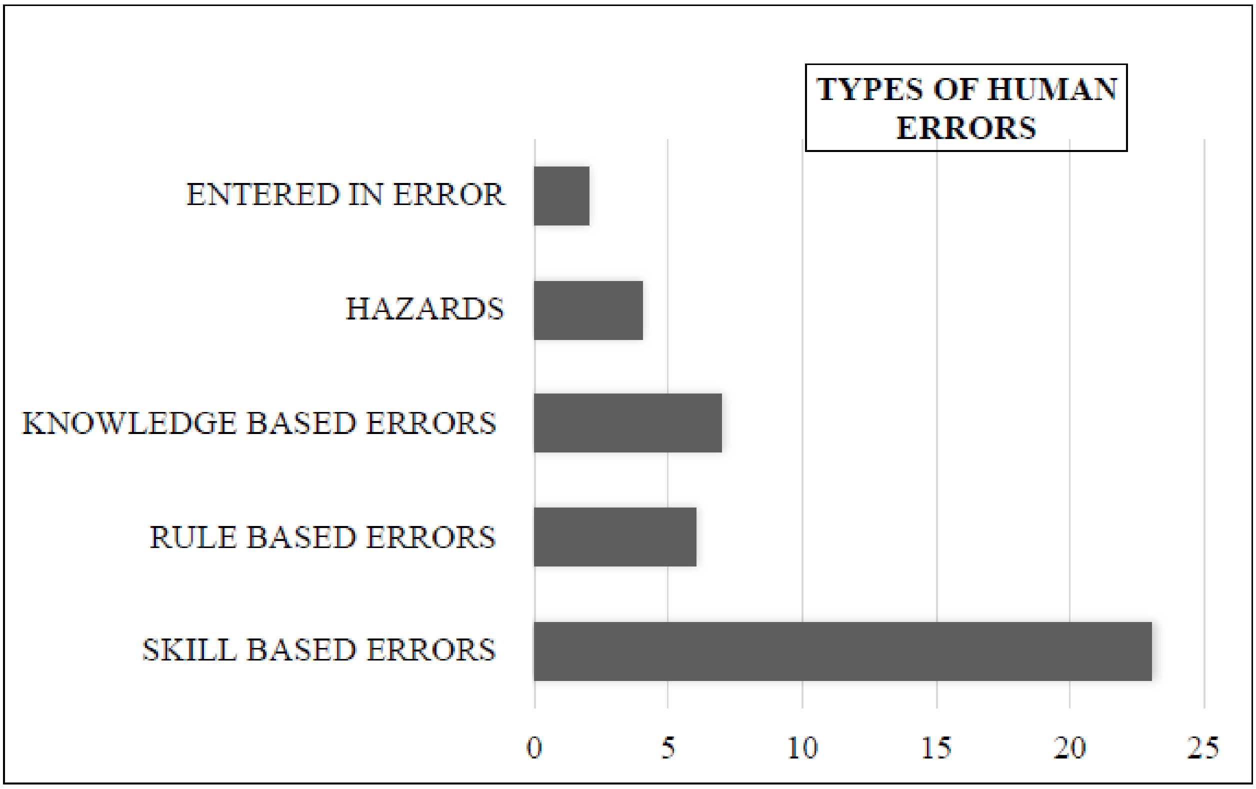

Figure 2. Types of Human Errors, adapted from "Types of Human Errors Identified in this Research linked to Rasmussen's Taxonomy," by S.K. Dyer, 2020, Human Error and Interactions with Technology in Safety-Critical Workplaces: Learning from the Aviation Industry.

The details described exclusively in the skill-based incident reports shows that both pilots and engineers inadequately performed high consequence tasks and failed to demonstrate a skill, either due to inattention or due to insufficient tools or resources. The higher number of skill-based errors, significantly emphasized incidents of human error, primarily related to person-machine interface or what is commonly known in the industry as humans experiencing slips, trips or falls. Out of the skill-based errors, approximately 20% were associated with the pilots but the majority occurred in or around the maintenance hangar and were related to the human error experiences of the engineers. The rule-based errors (14%) appeared significantly less than the skill-based errors (55%) but there were less rule-based errors (14%) than knowledge-based errors (17%) which contradicts Rasmussen's findings who found more rule-based errors than knowledge-basederrors (Rasmussen, 1987). What was notable was that there was no mention of rule-based errors found in the interviews from either the engineers or the pilots. The knowledge-based errors (17%) were found to be slightly more than the rule-based (14%) and all the identified knowledge-based errors from my field research underscored the humans' misapplication of their knowledge due to a memory lapse or due to insufficient knowledge. So, in summary, the results of the data collected closely matched Rasmussen's research on SKR where more skill-based errors were discovered than rule or knowledge-based errors. Both engineers and student pilots made more skill-based errors than any other errors. Most markedly, the engineers were involved in *all* the rule-based errors and the pilots experienced *all* the knowledge-based errors.

Discussion

Many safety-critical organizations appreciate that effectively engaging and developing humans to ensure that they are competent enough to carefully perform high consequence tasks involves assessing their level of skills, knowledge of their tasks and familiarity with the rules and regulations of their particular industry (Dekker, 2017; Hollnagel, Woods & Leveson, 2006). In order to mitigate human error, of course it is essential for safety-critical organizations to close the skills gap, to re-train and re-enforce company policy so that these skills, rules and knowledge are firmly in place.

However, humans have an enormous capacity to accomplish complex tasks and draw upon strengths that reach far beyond merely following rules, building their skill set or gaining knowledge about their particular job. Ultimately, I found that neither Rasmussen's SKR taxonomy nor other literature reviewed, completely covered what appears to be a type of human error thatemerges when humans try to improve safety but their ideas are not communicated clearly within their own industry environment. Humans have the capacity to be inventive and innovative and more importantly can demonstrate a desire to challenge and autonomously improve their own performance. Humans are not robotic by nature but are social creatures who develop and grow their skills sets over their careers. Humans are personally and culturally driven by distinctly different standards and values and often generate unusual and new ideas that positively guide how they behave in the workplace. Humans, especially those who work in safety-critical workplaces on the frontline, like engineers and pilots, draw upon that distinctive resourcefulness on a daily basis to perform critical tasks, alone. At other times they work together to develop innovative ways of solving complicated problems that are exclusively connected to those critical tasks. Sometimes humans fail to speak up and communicate that innovative idea and this can be viewed as an innovation-based error as shown in Figure 3.

While humans are inventive and imaginative and often demonstrate the ability to revolutionize their critical tasks, they actually need a venue that allows them to be openly acknowledged to communicate those innovative ideas. It is the responsibility of the safety-critical organizations to encourage those humans who are working at the sharp end to unreservedly volunteer their opinions and innovative ideas (Donovan, Salmon, Horberry & Lenné, 2018; Tucker & Tucker, 2015). Creating the right conditions and providing a comfortable environment for a human to share their thoughts and feel safe enough to have a voice to discuss their ideas is imperative for safety-critical organizations (Brache & Rummler, 2013; Detert & Burris, 2016; Edmondson, 1999, 2003, 2018; Nemeth, 1992; Schwartz & Wald, 2003; Ward, Ravlin, Klaas, Ployhart & Buchan, 2016). So, as shown in Figure 3, innovation-based errors can occur when the safety-critical organization overlooks or disregards the ideas of individual humans. If the safety-critical organization does notopenly and transparently provide that backdrop for their humans to contribute, then this could be viewed as the organization failing to implement an innovation.

CLASSIFICATION OF HUMAN ERROR R.I.S.K.				
ERRORS	Rule Based Errors	Innovation Based Errors	Skill Based Errors	Knowledge Based Errors
HUMAN FAILS TO:	follow an effective rule	communicate innovation	pay attention (slips, trips, falls)	remember information
ORGANIZATION FAILS TO:	issue an effective rule	implement innovation	provide sufficient resources	provide correct information

Figure 3. R.I.S.K. Innovation Based Errors, adapted from "R.I.S.K. Classification of Human Error," by S. Dyer, 2020, Human Error and Interactions with Technology in Safety-Critical Workplaces: Learning from the Aviation Industry.

Conclusion

This research studied a small number of humans in specific circumstances, dealing with particularly sensitive safety-critical issues, with the human preserved at the center of the wider safety-critical organizational context. The main strength of this malleable design was to show that humans possess more than just physical skills, an appreciation of the rules and knowledge of how to undertake a task. In fact, humans have unique social, emotional and psychological traits that enable them to complete complicated, multifaceted critical tasks and at the same time, show they are intrinsically motivated to mitigate error and resolve problems self-sufficiently. Also, throughout the research experience we embraced the over-arching the notion that humans who work in safety-critical organizations are deeply connected and auspiciously share the identical interpretation of human error, that it is inevitable.

So, if we consider Plutarch's remark 'To err is human…' and reason that it holds some conviction, we must also believe that humans do not turn up for work every day in their safety-critical workplace with the intention to harm themselves, others or the equipmentaround them. With this noble idea in mind, that making human errors is a natural phenomenon and that humans are socially intelligent creatures, this research carefully measured the SKR human error classification system against the existing state of human errors found at a research site, a GA private air charter business. The research uncovered a missing link in the SKR human error model, showing that humans in the workplace are made up of more than skills, knowledge and rules-based errors but also habitually practice innovation-based errors. Sometimes resistance to innovative ideas stem from the individual human, other times the innovation-based errors come from the leaders in the safety-critical organization who disregard the opinions of the individual. To conclude, we acknowledge that it could be viewed as excessive for the GA industries to implement developed machinery such as AR into their safety-critical workplaces, to combat human error. Yet, for the sake of our enthusiasm for developed technologies to be thrust to the foreground in GA industries, we suggest that the HRD practitioner's role is fundamental in better engaging humans to build stronger communities of practice within GA, in order to maintain a continued sense of technological data sharing and curiosity in how these technologies might help reduce human error in the future.

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No potential conflict of interest was reported by the authors.

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