The influence of mental workload in causes of system degradation in air traffic control

System safety and resilience is a critical concern in the air traffic domain. An important element of maintaining system safety and resilience is the ability of systems to 'degrade gracefully'. However, previous research on the causes of system degradation in the air traffic domain are sporadic, and the potential interaction between the causes of degradation, and the resulting possible compound effect on the entire system, has been under-researched. An interview study was conducted with 12 retired controllers as participants. The results of a thematic analysis revealed the key causes of system degradation, and the associated impact on the ability of the controllers to prevent system degradation or recover the system. Findings have direct implications for identifying and mitigating potential risks of increasingly automated air traffic control systems.

INTRODUCTION

Within the air traffic domain, initiatives such as the US-focused NextGen and the Single European Sky Action Research (SESAR) program in Europe are enabling significant change in air traffic management operations. Technological advancements, increased focus on automation, airspace redesign and a redefinition of the control operations are a few of the areas that may be impacted. With such fundamental change to the air traffic management system expected in the near future, system safety and resilience (e.g. Hollnagel, 2010) is a critical concern. An important element of maintaining system safety and resilience in air traffic is the ability of systems to 'degrade gracefully'. A system that is designed to degrade gracefully can "tolerate failures by reducing functionality or performance, rather than shutting down completely" (Shelton, Koopman & Nace, 2003, p111), a necessity in a domain in which there are no physical barriers or defenses to protect aircraft in flight. It is therefore essential that the future air traffic system is designed to have the capability to degrade gracefully.

Of the available graceful degradation research, especially within the complex human-machine systems such as air traffic management (ATM), a majority of studies have focused primarily on the impact of technological causes of degradation and the ability of technology to prevent degradation. Although these research areas have provided excellent insight into the role of technology in gracefully degradation, non-technological causes of degradation (such as those arising from a non-optimal environment or from human operators), as well as contributions to degradation prevention or recovery, have been relatively neglected (Edwards & Lee, 2017). In an environment such as ATM, environmental factors, technological systems, and human operators are highly interconnected and can all influence the ability of a system to degrade gracefully. The current understanding of gracefully degrading systems is therefore largely out of step with real-world contexts, preventing an ecologically valid understanding of the causes of degradation, the tools and methods that prevent system degradation, and recovery of the system online.

After a systematic review of literature relating to graceful degradation in complex systems, (Edwards & Lee, 2017) applied a human-systems integration approach to develop a framework of graceful degradation. This framework suggested that there were four main elements of graceful degradation – a degradation cause, identification of the degradation, prevention of impact on the system, and, if degradation occurred, recovery of nominal operations. Findings revealed that causes of degradation could be broadly categorized into technological fault or failure, the environment, or human operators. The review identified that research within each of these categories is highly independent and did not cross domains. As a result, the potential interaction between the causes of degradation, and the resulting possible compound effect on the entire system, was under-researched. In addition, (Edwards & Lee, 2017) identified a gap in research relating to the contribution of human operators in a gracefully degrading system. Human operators such as controllers, were expected to prevent degradation, or recover a degrading system once technological solutions were no longer viable, such as in aircraft emergencies, and failures or faults in software and hardware. However, the specific techniques or approaches used by human operators to contribute to degradation prevention or system recovery, were under-specified. As a result, understanding was limited regarding the performance limits of the human operator, and the conditions under which human operators would, or would not, be able to contribute to the prevention of degradation, or recovery of a degraded system.

The current research aimed to contribute further understanding to research gaps identified by (Edwards & Lee, 2017), and review and extend the proposed framework of graceful degradation. The current research had three specific aims. First, the research aimed to investigate causes of degradation in ATC (across all categories of technology, environment, and human). A second aim was to investigate the relationship, and potential interactions, between triggers of degradation across the technology, environment and human operator categories, and the association with controller performance. The research also aimed to inform fundamental understanding of prevention and recovery of degradation in the current ATC system, with a specific focus on the contribution of ATCOs.

To address the aims, a qualitative interview exercise was conducted with retired en-route and TRACON ATCOs. Two specific forms of knowledge elicitation techniques were used; a general interview focused on participants' past experience, and a scenario-focused knowledge-elicitation exercise. The use of multiple techniques allows weaknesses of individual techniques to be addressed, as well as adequately addressing separate study aims. Finally, the use of multiple techniques has the advantage of collecting data in different ways to inform the same aim, potentially providing a more detailed understanding.

METHOD

A total of 12 retired TRACON and en-route controllers participated in two qualitative exercises, totaling 2.5 hours. Participants volunteered to participate, so the sample was based on a self-selected sample. However, all participants were required to have experience in an en-route or TRACON environment. The number and length of exercises, as well as the number of participants, was based on pragmatic considerations. The first exercise was a semi-structured interview relating to the controllers' previous experience, lasting one hour in length. In the first exercise, participants were first asked about their experience of the common causes, or triggers, that could result in degradation. Participants were then asked to list, in their experience, both existing practices for how these causes can be mitigated, and also their one strategies for mitigating system degradation impacts. Participants also answered questions regarding the affects of human factors of workload and fatigue on the causes of degradation and recovery.

The second exercise utilized a semi-structured interview methodology, although this time responses were targeted to specific scenarios. The objective of this exercise was to understand the occurrence and impact of interactions between triggers of degradation. Controllers were asked how a specific technological failure would be likely to impact performance, and then how a specific environmental event would impact performance. Controllers were then asked about the possibility and likely outcome of these two examples occurring together. A protocol was used to standardize the interview procedure for both exercises. Interview schedules were developed to guide the semi-structured interview; participants were asked pre-designed lead questions which were then followed by probes. The two independent qualitative exercises provided different benefits to the study. As the first exercise related specifically to controllers' experience, this provided breadth of information and enhanced generalizability of the data. However, as the information was based on experience, there was also a possibility that the controllers' experience would be so diverse that comprehensive data on specific topics may not be gained. In order to address this potential limitation, a second qualitative exercise was used in which questions were focused on specific air traffic scenarios. By grounding the questions to the same scenario for all controllers, it created the opportunity for the comparison of data between each focused scenario.

Participants

In total, 12 TRACON and en-route controllers were interviewed. All participants were male. This was a result of the convenience-based sampling method, and not through design. All participants worked as en-route controllers in the bay area. Participants has been based in one of three areas: Bay TRACON (2 controllers, 17%), Oakland enroute center (9 controllers, 75%) and Los Angeles center (1 controller, 8%). Participants' ages ranged from 51-72. Participants responded to grouped age ranges and so an average age could not be calculated. A total of five participants (41.6%) were in the 51-60 ages range, six participants (50%) were in the 61-70 age range. One participant (8.3%) responded to the 61-72 age range. All participants were qualified ATCOs who had completed training. Years of experience as an ATCO (excluding training) in TRACON and En-route control ranged from 10-35 (M=27.42, SD=7.82). All 12 participants had worked as an on the job training instructor (OJTI). Years of experience as an OJTI ranged from 15-33years (M=25.45, SD=7.88). In total three participants were also supervisors. Experience as a supervisor ranged from 3 to 17 years (M=11 years, SD=7.21).

Materials and Equipment

Exercise 1: Semi-structured interview

An interview schedule was designed to structure the interview. The interview comprised of 12 lead, open-ended questions which related to four areas of interest:

1. Impact and recovery of environmental off-nominal events (e.g. thunderstorm, aircraft emergency)
2. Impact and recovery of tool or automation failures (e.g. Radio or radar failures, conflict probe errors)
3. The occurrence and impact of Interactions between environmental and technological off-nominal event
4. Strategies to recover degradation

The second exercise focused specifically on examples of interaction between causes of degradation.

Lead questions were arranged from general topics (e.g. "Could you please tell me about a time in the recent past when you experienced a non-optimal environment, such as a thunderstorm or aircraft emergency") to more specific questions (e.g. "what are your control strategies for off-nominal situations?"). Examples of common triggers of degradation (technical and environmental) were used in the lead question to facilitate participants' understanding. The same indicators were used in examples for all participants (Millward, 2006). Interview schedules were reviewed and approved by a human factors expert and two ex-controllers. The interviews were recorded on two Olympus DSS Standard digital recorders.

Procedure

The participant was welcomed to the interview room and provided with a standardized brief. The participant was then asked to sign an informed consent form if he/she was happy to continue, and completed a demographic questionnaire. The first exercise began with an open question, followed by several probes. Once the interview was complete, the participant received a 30 minute break The participant was then welcomed back in the interview room. The participant was presented with a total of 3 air traffic scenarios, and asked open questions on each scenario. After 1 hour, the participant was thanked for his/her time and given a standardized debrief which contained the researcher's contact details.

Strategy of analysis

Interviews were transcribed orthographically. The level of detail resulting from orthographic transcription was sufficient for the aims of the research and method of analysis. Only the words that were spoken were captured in the transcription. No paralinguistic features were captured (such as sighing, intonation) (Strauss & Corbin, 1997; Wilkinson, 2004) Thematic analysis was selected as the analysis strategy (5). In line with the thematic analysis procedure (Strauss & Corbin, 1997; Wilkinson, 2004) the transcripts were read through, and elements of participant responses that were related to the aims of the study were identified. The transcripts were then re-read with the aim of categorizing the identified elements into emerging themes. No identifying information was stored in the transcription. Where quotations are used, participants remain anonymous.

RESULTS AND DICUSSION

For brevity, a subset of the most operationally relevant results of the interview study are presented below.

Causes of system degradation

Identified causes of potential degradation broke down into three main categories: technology-related, environment-related and operator-related. This was in line with Edward and Lee's (2017) findings, and confirmed this portion of the proposed framework of graceful degradation.

Technological causes. Equipment failures were, in general, felt to be common, and ranged from extremes of total failure of critical tools such as radar and radio communications, to smaller, incremental failures. Controllers reported that the extent of the impact of the failure on operations was related to the function; for example, tools such as navigation aid failures were not felt to have a large impact due to the available backup systems still showing navigation points. Controllers could then use strategies to prevent any noticeable impact to ATC operations. However, with technology that was critical to the operation, such as loss of radar or radio communications, operations were more likely to be reduced or even stopped, affecting efficiency but not safety.

A distinction was made between limitations of technology, and failures of technology. Failures of technology were described as a loss of the designed function of the tool or automation, such as a tool that was not working or failure of radio communications. Conversely, technology limitations represented technology that was functioning as designed, but was only helpful if used in a specific way; using not as intended could create a negative impact to the operation. One participant gave the example of 'leader lines' which is intended to be a predictive tool that can show the controller where the aircraft will be in a selected number of minutes into the future if the aircraft contributes on its current trajectory. The participant described a situation in which a false conflict alert was given when aircraft that were on a conflicting trajectory were turned, as the leader lines did not take into account the turn of the aircraft: "*You know they don't curve. They only go straight. So you also know that the flashing data block conflict is all based on where he is currently heading, even though you know you are turning"*. Without this knowledge, it would be harder to differentiate an actual conflict, leading to increased workload and distraction. A participant also said *"There were certain technologies where you knew they had some sort of limitation to them. And then you understood that so you didn't push it to the limit."*

This is an important distinction – if the controllers understood the 'limitations' of the technology they were working with, they could use the technology appropriately. However, if they did not use tools within the intended design capabilities, it had the potential to negatively impact operations as much as a tool that had failed.

Environmental causes. Causes of degradation that could result from the environment could be further subcategorized into causes that were known background factors of the operation function, or dynamic causes which emerged minute by minute. Causes that were stable included the airspace design (*"Some sectors have inherently a difficult part of the sector"*), the traffic presentation (*"you could have four, five airplanes and you feel busy, because they all came out boom, boom, boom, boom, right behind each other"*) and active military areas, which reduce the airspace available and therefore the flexibility that the controller has to manage traffic. More dynamic triggers that could result in system degradation included adverse weather, such as thunderstorms, (*"You're a little more worried about everything. You have to scan more intently; it's more stressful. it's more of an uncontrolled scenario"*) and aircraft emergencies (*"Something hit his window and his window cracked. It was about to pop out. So he is diving"*). Each one of these alone didn't necessarily create system degradation; however, if the controller was already dealing with a large amount of complex traffic, the addition of these variables would take time and flexibility away from the controller, adding to an increase in workload.

Human operator. Many factors that resulted from working within a team were identified to affect system performance. Miscommunications with pilots created workload for controllers, with one participant giving an example of a language issue: "*it's a language issue, you can't understand what they're saying. Or, they can't understand what you're saying"*. Repeating instructions due to a lack of clarity or cross-talk on the radios would also have an impact: *"I was busy in that I did not have time to keep repeating things"*. Performance influencing factors could also affect controller performance, and by association, system performance. Factors such as stress (*"I would have to say that stress is the biggest thing that builds and it is really high at the start of your career"*) workload (*"anything that is a change (creates workload). Potentially you could argue that somebody who requested a change in altitude increases workload"*) and fatigue (*"Tired obviously plays into everything. I guess that makes it harder when you're tired,* *doing the regular, ordinary, routine stuff"*) were the most common factors that were raised. All controllers talked about strategies that could be employed to mitigate the impact of these factors that would reduce the potential impact to the system, although this was dependent on identifying the issue created by the performance-influencing factors.

Interactions of causes of system degradation

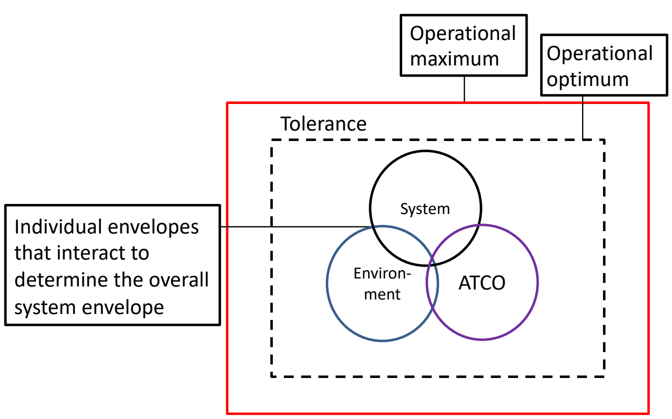
An important point was repeatedly raised by participants that in general, the control strategies that they applied could mitigate most causes of degradation, and would not necessarily have an identifiable impact on the operation. Controllers considered this 'on-line' prevention as 'part of the job' and 'what they are paid to do'. However, an interesting point was raised that interactions can take place between the causes of potential system degradation. The majority of controllers described this as the 'snowball effect', where multiple, small things can happen at a time. One controller descried situations that were "*just a whole mess of everything that went weird",* including the following example: *"It was just a lot of airplanes all flying and it was just really busy…because I turned that guy northbound to the left I may have created another crossing scenario from the guy behind him it can have a snowball effect"*. Interactions could occur between any and all of the specific causes, such as a busy, complex environment, with bad weather (environmental), associated with increasing workload and fatigue (human operator) at the same time as a tool malfunction was occurring. A participant shared the following example: *"I have been in stressful situations (in complex traffic) where I was on the certification on the radar side one time and the computer flopped"*.

The critical point about these interactions was that each additional element, although somewhat easy to mitigate independently, added to increased workload and subsequently, increased the likelihood of a controller being pushed to their limits of performance. One participant described a situation that was highly complex, saying "***I****t wouldn't take much to really make you feel really stressful like, oh my God this is really out of control"*.

The operational envelope

The result of interactions between various incremental issues has the potential to create a compound affect on controllers. By understanding more about the interactive affects of these causes of system degradation, as well as the mitigation strategies that are used, more accurate prediction of when controllers are more likely to reach their limits of performance is possible (see figure 1). In addition, it then becomes more possible to specify a trade space for future system design that takes into account the potential for these interactions, to ensure that the system does not reach a degradation point under such circumstances. The impact of the cumulation of these individual components can be mostly easily predicted based on an understanding of the current cognitive resources of the ATCOs (influenced by state, environment, outside concerns) as well as the additional demand placed on the controllers as a result of the technological and environmental conditions.

Figure 1. Concept of the operational envelope



Degradation mitigation: The critical role of controllers

Controllers are active in their environment, and create and implement mitigation strategies that are used to prevent operational system degradation, or even recover from system degradation. A distinction was made between prevention of system degradation and recovery of the system after degradation. To prevent system degradation, controllers adapt their control strategies to the given environment. If there is a specific event, such as a technology failure or an unexpected action in the airspace or weather, controllers *"resort back to fallback positions. A lot of it becomes stuff you learned through your experience"*. The strategies are diverse, and dependent on the situation. For example, one controller described a strategy that he used when dealing with a thunderstorm "*We try to fan them out…so he can fly the speed he wants to without overtaking the guy ahead of him*". Although the thunderstorm reduced the amount of airspace available, this strategy would support the maintenance of both efficiency and safety, so that the weather would have as little impact on the system as possible. Controllers therefore have a critical role in preventing the many causes of potential degradation from impacting the wider system.

When the operational system is degraded by an event, such as a radar or communications failure, controllers utilize control strategies to minimize the impact on the system, to ensure the system can degrade gracefully , and ultimately recover. One controller described a situation where both radio communications and radar abilities had been lost in one center. In this case, some of the strategies utilized were stopping departures "*so you don't pump more aircraft into a scenario that is less controlled*", and through teamwork, controllers in other centers took over radio communications "*They have expanded role. They adjust the range on their scopes so they can see out a ways and they will grab them*". In such an extreme case, even though efficiency was affected, these strategies maintained safety and also allowed complete recovery of control once the tools were again functional.

Implications for future systems

Future systems for ATM generally highlight the increased use of automation, reduced flexibility and increased precision of aircraft (FAA, 2014). Findings have implications for the role of controllers. If the role of controllers is to continue mitigating the potential impacts of causes of degradation, controllers will need to have the flexibility and time to be able to implement these strategies. In addition, there are greater implications for how controllers will contribute to a graceful degradation of the system and recover the system with more automation technologies. In addition, the prediction of when operator or system state may be more likely can be predicted by considering the current system state and understanding the potential load on the controller. A key point of consideration when designing future systems, is therefore to ensure that when failure or other degradation causes occur, prevention of system impact, or system recovery, can be maintained through the collaboration between the human operator and system.

Conclusions

ATCOs have a critical role in online prevention of system degradation resulting from technological, environmental and human operator causes. The study provided insights into the causes of ATC system degradation, as well as the controllers' role in online mitigation of the impact of these causes, and their role in the graceful degradation of the system. An initial concept of a system envelope was developed from the results of the study, highlighting the interactive effect of the causes of degradation, and the resulting impact on controllers. Future research should explore whether interacting causes of degradation has a compound or cumulative affect on controllers and the wider system, and how this accumulation impacts controller performance. In addition, the notion of an operational trade-space that can support the design of future systems within tolerance must be explored future in order to predict when system degradation is most likely, and mitigate the causes, to prevent the potential system-wide consequences to safety and efficiency.

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