Safety in aviation has been historically defined in terms of the occurrence of accidents or recognized risks; that is, safety is typically defined in terms of things that go wrong. An alternative and complementary approach is to focus on what goes right, and identify how to make that happen again. Focusing on the rare cases of failures attributed to “human error” provides little information about why human performance almost always goes right. Similarly, focusing on the lack of safety provides limited information about how to improve safety. This work builds upon a growing literature on resilience engineering and new approaches to safety (Hollnagel, 2014; Hollnagel, Woods, & Leveson, 2006). Data were collected from commercial airline pilots and air traffic controllers that illustrate the prevalence and value of resilient behaviors observed as routine in everyday operations. Results of data analyses as well as approaches to identify novel methods for data collection on resilient behavior for use in development of in-time safety monitoring, prediction, and mitigation technologies are described.

Every day in aviation, pilots, air traffic controllers, and other front-line personnel perform countless correct judgments and actions in a variety of operational environments. These judgments and actions are often the difference between an accident and a non-event. Ironically, data on these positive behaviors are rarely collected or analyzed. Data-driven decisions about safety management and design of safety-critical systems are limited by the available data, which influence how decision makers characterize problems and identify solutions. In the commercial aviation domain, data are systematically collected and analyzed on the failures and errors that result in infrequent incidents and accidents, but in the absence of data on behaviors that result in routine successful outcomes, safety management and system design decisions are based on a small sample of non-representative safety data.

NASA has proposed development of in-time safety monitoring, vulnerability prediction, and incident mitigation technologies for civil aviation (NASA, 2017). Ironically, a critical barrier
to measuring safety threats and the impact of mitigation strategies in ultra-safe systems like commercial aviation is the lack of opportunities for measurement of beneficial events and conditions. Although it is common practice to relate safety to how many accidents or fatalities occur for a given number of flights, very safe systems have very few accidents. Therefore, accident data cannot be readily used to validate safety improvements for at least two reasons. First, the time necessary to observe the effect of a given safety intervention within accident statistics becomes excessively long, with estimates up to 6 years for a system with a fatal accident rate per operation of $10^{-7}$ (Amalberti, 2001). Second, attributing improvement to a specific intervention becomes intractable due to the many thousands of changes that a complex sociotechnical system would experience over that same time period (Nisula, 2018).

Historically, safety has been consistently defined in terms of the occurrence of accidents or recognized risks (i.e., in terms of things that go wrong). These adverse outcomes are explained by identifying their causes, and safety is assumed to be restored by eliminating or mitigating these causes. An alternative to this approach is to focus on what goes right and identify how to replicate that process. Focusing on the rare cases of failures attributed to “human error” provides little information about why human performance routinely prevents adverse events. Hollnagel (2014) has proposed that things go right because people continuously adjust their work to match operating conditions. These adjustments become increasingly important as systems continue to grow in complexity. Thus, the definition of safety should reflect not only “avoiding things that go wrong,” but “ensuring that things go right.” The basis for safety management requires developing an understanding of everyday activities. However, because few mechanisms to monitor everyday work exist in the aviation domain, there are limited opportunities to learn how designs function in real operational conditions.

This concept of safety thinking and safety management is reflected in the emerging field of resilience engineering. According to Hollnagel (2016), a system is resilient if it can sustain required operations under expected and unexpected conditions by adjusting its functioning prior to, during, or following changes, disturbances, and opportunities. To explore “positive” behaviors that contribute to resilient performance in commercial aviation, a range of existing sources of data about pilot and air traffic control (ATC) tower controller performance were examined, including subjective interviews with domain experts and objective aircraft flight data records. These data were used to identify strategies that support resilient performance and methods for exploring and refining those strategies in system-generated data.

**Analysis of Operator-Generated Data**

Pilot and ATC tower controllers were interviewed to elicit specific examples of resilient performance in routine operational situations. This approach focused on identifying behaviors and strategies based on the specific lived experience of the participants in an attempt to focus as closely as possible on work-as-done rather than work-as-imagined or work-as-designed.

**Method**

**Participants.** Twenty-one airline pilots and 12 air traffic controllers were recruited to participate. All pilot participants were employed by a major airline operating under Federal Aviation Regulations part 121 or its foreign equivalent. All controller participants were highly experienced, with an average of 33 years on the job. Interviews were conducted under approval from NASA’s Institutional Review Board.
Procedure. Participants were interviewed individually, using a semi-structured protocol designed to elicit specific instances of unplanned or unexpected events experienced during routine operations, as well as their goals, motivations, pressures, and knowledge at the time of the described actions. Each interview lasted approximately 45 minutes.

Controller participants also completed a written questionnaire, in which they estimated the frequency of behaviors associated with resilient performance. In addition, controller participants took part in focus group discussions after completing their interview and questionnaire. Because pilots were interviewed during time-limited breaks between flights, they were not asked to complete the questionnaire nor participate in focus group discussions.

Results

The events and behaviors that participants described in the interviews were used to extrapolate strategies for resilient performance organized around four capabilities of resilient systems: anticipating, monitoring, responding, and learning (Hollnagel 2011). These strategies are shown in Table 1.

Table 1. Identified Resilient Performance Strategies Employed in Routine Aviation Contexts.

<table>
<thead>
<tr>
<th>Capability</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticipate</td>
<td>Anticipate procedure limits</td>
</tr>
<tr>
<td>Monitor</td>
<td>Monitor environment for cues that signal a change from normal operations</td>
</tr>
<tr>
<td></td>
<td>Monitor environment for cues that signal need to adjust/deviate from current plan</td>
</tr>
<tr>
<td></td>
<td>Monitor own internal state</td>
</tr>
<tr>
<td>Respond</td>
<td>Adjust current plan to accommodate others</td>
</tr>
<tr>
<td></td>
<td>Adjust or deviate from current plan based on risk assessment</td>
</tr>
<tr>
<td></td>
<td>Negotiate adjustment or deviation from current plan</td>
</tr>
<tr>
<td></td>
<td>Defer adjusting or deviating from plan to collect more information</td>
</tr>
<tr>
<td></td>
<td>Manage available resources</td>
</tr>
<tr>
<td></td>
<td>Recruit additional resources</td>
</tr>
<tr>
<td></td>
<td>Manage priorities</td>
</tr>
<tr>
<td>Learn</td>
<td>Leverage experience and learning to modify or deviate from plan</td>
</tr>
<tr>
<td></td>
<td>Understand formal expectations</td>
</tr>
<tr>
<td></td>
<td>Facilitate others’ learning</td>
</tr>
</tbody>
</table>

In responses to the administered questionnaire, all controller participants indicated that they exhibited resilient performance on the job as air traffic controllers, with 83% (N = 10) estimating that this occurs “at least once per session,” where a “session” refers to each one of the multiple times that a controller works at their position during an 8-hour daily work shift.

Results showed that 75% of controller participants (N = 9) stated that they make traffic management decisions not explicitly specified within policies or procedures (e.g., FAA Order JO 7110.65, facilities standard operating procedures, letters of agreement) “at least once per week” with 58% (N = 7) estimating the occurrence to be “at least once daily.” When asked, “How many
of these decision would you categorize as ‘resilient’ decisions?’, 75% estimated “more than 50%” (N = 9), and 58% indicated “more than 90%” (N = 7).

In focus group discussions with the controller participants, all stated that they had filed incident reports through one or more safety reporting systems. However, none of the participants stated that their narrative descriptions focused on detailing positive behaviors that demonstrate resilient performance. Participants noted “it was their job” to adapt to routine disturbances, and showing resilient behavior was “what they get paid to do.” Participants believed that, in the current cultural environment, controllers might be reluctant to file positive incidents except in the case of extraordinary performance. Another barrier to positive event reporting is that most reporting systems are structured to capture negative events (i.e., when things go wrong). Participants suggested providing guided assistance for furnishing narrative details to ensure that filed reports focused on desired aspects or features of resilient performance.

**Exploring Identified Resilient Strategies in System-Generated Data**

Although operator-based data (e.g., structured interviews and self-reports) can provide rich data with regard to intentions, goals, pressures, or operator state, recollection-based approaches are subject to reconstructive attributes of human memory (Schacter, 1989). Examination of system-based objective data can substantiate subjective accounts and provide quantifiable details about events that are difficult or impossible to obtain from subjective data alone.

Based on the strategies and behaviors identified through operator interviews (see Table 1), the authors considered how these strategies might show up in aircraft flight data. For example, operators “anticipating resource gaps” might manifest in objective aircraft flight data as the pilot taking action to preempt an anticipated adverse state (i.e., a state indicating that one or more resources had reached their functional boundaries). These preemptive actions were identified using a machine-learning algorithm called deep temporal multiple instance learning (Janakiraman, 2018). This algorithm was designed to detect “precursor” states, ahead of a predefined known adverse event, that have a high probability of predicting that adverse event.

This method was demonstrated using Flight Operations Quality Assurance (FOQA) data. Commercial airlines with FOQA programs use data from flight data recorders to monitor daily operations. The adverse event used in this example was a high-speed exceedance at 1000 feet. A sample of 500 adverse event flights and 500 non-event flights were analyzed. Adverse event flights were analyzed to characterize those events based on 60 recorded variables, and non-event flights were then examined for high precursor probabilities.

An example of a flight that exhibited high precursor probability followed by the lowering of that probability is shown in Figure 1. The x-axis shows distance in nautical miles (NM) from the point at which the aircraft reaches 1000 ft. altitude. The solid blue line is the time series trace for the selected parameters that describe the precursor. The black dotted lines indicate the 10th-90th percentiles of the non-event data for each parameter for 0.25 NM binned distances to the event. Plot 4 shows the computed precursor score that the algorithm provided for each sample of the time series. Samples for which the precursor score was greater than 0.5 are marked with red dots in Plots 1-3 and are considered high-probability precursors of a high-speed exceedance at the end of the time series. The shaded green region in the precursor score plot represents the event of interest, in which a degraded state was identified and potential for a preemptive action was indicated.
Figure 1. Time series plots for vertical speed, altitude, computed airspeed, and precursor score are depicted for a flight in which a preemptive action (i.e., slowing descent rate) was taken to avoid a high-speed exceedance at 1000 ft.

In Figure 1, the descent rate, inferred from vertical speed, was significantly faster than the normal distribution at that point in the flight (Plot 1). Simultaneously, the airspeed was trending upward toward the upper bound of the nominal distribution (Plot 2). At this point, the pilot slowed the aircraft’s descent rate and the airspeed began to hold steady. Although the airspeed remained outside the normal distribution, the transfer of the aircraft’s energy from potential (i.e., altitude) to kinetic (i.e., airspeed) reduced the probability of a high-speed exceedance adverse event. When aircraft energy is converted from altitude to speed, more tools available to the pilot to reduce kinetic energy, for instance through use of speed brakes, deploying flaps, etc.

FOQA data can provide many quantitative details about operator and vehicle performance, but cannot provide information about the knowledge state, motivation, or broader context for the event. Why was the pilot flying the arrival at a higher than normal airspeed? What contextual cues triggered the pilot to take action? If there were multiple appropriate actions that could have been taken, why did the pilot select that specific action? The answers to these questions could be obtained through observer- and operator-based data to supplement system-based data and provide a more complete understanding of work-as-done.

Discussion

This study highlighted the value and feasibility of learning from what goes right in addition to what goes wrong. To move forward in this area of research, the authors propose the following recommendations for the aviation safety community:

- Redefine safety in terms of the presence of desired behaviors and the absence of undesired behaviors.
- Leverage existing data to identify strategies and behaviors that support resilient performance.
- Develop tools to capture new operator-, observer-, and system-generated data on strategies and behaviors that support resilient performance.
- Develop a system-level framework for integrating insights from various data types to facilitate understanding of work-as-done.
• Develop organization-level strategies that promote recognition and reporting of behaviors that support resilient performance.

Through understanding “how” and “why” people perform successfully in a variety of circumstances, in addition to understanding “what,” “where,” and “when,” systems can be designed to ensure the ultra-safe airspace system is not unintentionally made less safe due to loss of resilient properties provided by human operators yet are not well-understood.

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