2009

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Repository Citation

Hooey, B. L., Wickens, C. D., Salud, E., Sebok, A., Hutchins, S., & Gore, B. F. (2009). Predicting the Unpredictable: Estimating Human Performance Parameters for Off-Nominal Events. *2009 International Symposium on Aviation Psychology*, 202-207.
https://corescholar.libraries.wright.edu/isap_2009/81

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PREDICTING THE UNPREDICTABLE:
ESTIMATING HUMAN PERFORMANCE PARAMETERS FOR OFF-NOMINAL EVENTS

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A parameter meta-analysis was conducted to characterize human responses to off-nominal events. The probability of detecting an off-nominal event was influenced by characteristics of the off-nominal event scenario (phase of flight, expectancy, and event location) and the presence of advanced cockpit technologies (head-up displays, highway-in-the-sky displays, datalink, and graphical route displays). The results revealed that the presence of these advanced technologies hindered event detection reflecting cognitive tunneling and pilot complacency effects.

The next generation of the National Airspace System (NextGen; JPDO, 2007) is expected to require new technology to enable operations such as flexible 4-D trajectories, closely spaced parallel approaches, reduced aircraft wake vortex separation standards, equivalent visual operations, precision spacing and merging, and tightly-coordinated taxi operations. Some of the flight deck technologies that are anticipated with the transition to the NextGen include the use of head-up-displays (HUDs), highway-in-the-sky (HITS) displays, datalink, and graphical routing information. To ensure that these new technologies and operations are robust to system perturbations (Burian, 2008), it is important to ensure that they support pilot performance in both nominal and off-nominal conditions. Off-nominal conditions may range from 'less-likely but necessary' operations that are slightly outside the range of normal operations (such as conflict alerts and unpredicted weather events), to very rare events (such as aircraft trajectory blunders and equipment failures). An inappropriate response to an off-nominal event can lead to a cascading effect in the system and disrupt the entire airspace flow. Therefore, a challenge facing the aviation research community is the need to predict pilot performance in the face of off-nominal events.

Due to the unexpected nature of off-nominal events, the opportunities to collect pilot response data in human-in-the-loop (HITL) simulations are often limited to one data point per subject, which both limits the ability to draw valid conclusions and to generalize the findings to other events and scenarios (Wickens, 2001). Human Performance Models (HPMs) are research tools that have been used to evaluate pilot performance under nominal conditions and are often cited as a solution to examine off-nominal scenarios (see Foyle & Hooey, 2008). To date, however, models of off-nominal or unexpected scenarios are limited because insufficient data exist to characterize performance and populate the models. This research effort aimed to extract and extrapolate data from existing HITL studies to inform the development of HPMs of off-nominal scenarios. The scope of this research was limited to off-nominal events with clear, unambiguous onsets and clearly defined responses. It is asserted that human responses to these types of off-nominal events are human performance primitives that transcend task environments and thus are inherently well suited for inclusion as inputs to HPMs.

Method

A comprehensive review of the literature identified 26[1] HITL simulation studies (see References and Gore et al, 2009) that met the following criteria:

- The study was either a simulation or flight test with human pilots as subjects and sufficient detail was provided to discern the method used and the performance data
- Subjects had not received training regarding, or been cued to the possibility of, the off-nominal event
- The off-nominal event was either truly surprising (i.e., one per subject) or very infrequent (e.g., one per condition)
- The off-nominal event had a clear, unambiguous onset (e.g. warning light onset, traffic on runway) and an objective, measurable response (e.g., button press, eye glance, or verbal response)

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[1] A total of 34 papers were identified and summarized in Gore et al., (2009), however this paper focuses only on the 26 papers that provided miss rate data. Gore et al, 2009 also provides analyses of response latencies.

The review process yielded two types of events: 1) event onsets events, which required pilots to notice the presence of something such as the onset of a warning light or presence of an aircraft on the runway, and 2) error detection events, which required pilots to notice a discrepancy in a cockpit instrument or an invalid clearance from air traffic control (ATC). Both error types were included in these analyses. Events that required diagnosis of multiple cues, as opposed to simple event detection, were not included.

A parameter meta-analysis was conducted to pool pilot response data across multiple diverse HITL studies to increase statistical power and generalizability. The term parameter meta-analysis is used, because unlike a formal meta-analysis that averages *effect-sizes* across studies, it averages quantitative human performance parameters – specifically miss rates of off-nominal *event detection*. Response latencies were also evaluated, however, in most cases there were inadequate data to reach significance in the meta-analysis. These data are not presented here, but are available in Gore et al. 2009. The advantage of this parameter meta-analysis approach is that it produces estimates of response accuracy for each factor (represented as 'costs' or 'benefits' to the probability of detecting the event) rather than simply summarizing average miss rate for each particular off-nominal event. This method has previously been used to evaluate Synthetic Vision System (SVS) displays (Wickens, 2005), and human responses to imperfect diagnostic automation (Wickens & Dixon, 2007).

Analyses were conducted by pooling the event detection miss rate for common conditions across studies and weighting the studies by their sample size. For example, if two studies in one condition had miss rates of 1/5 and 30/50, a single proportion for the studies of 31/55 was extracted. Note that this mean proportion is far closer to the 0.60 value of the second study, than the 0.2 value of the first – but using this weighted approach, the resulting value more closely reflects the proportion of the larger sample size than if both studies had been given equal weighting. Chi-squared tests were used to assess if the relative frequency count of missed vs. non-missed events was statistically equivalent across the level of another variable. Subsequently, where appropriate, further chi-square tests were conducted to determine whether a difference observed might be modulated by a second factor. The modifications may occur when levels of another factor exert very different effects (i.e., a classic two-way interaction), and this modulation can be amplified if the *N* of the different studies contributing to the other factor is very different at its two levels.

Results

An analysis of the probability of a pilot failing to respond to the off-nominal event (that comprises the miss rate data), pooled across all available studies and event types, revealed an overall miss rate of 0.32, a value that is noteworthy for its magnitude above zero. All studies included in our analyses contained a positive indication of the off-nominal event, that is, the events were clearly visible, and hence certainly could be detected if they were expected and attention focused toward their location. This detection rate was further examined as a function of: 1) off-nominal event characteristics and 2) flight deck technology characteristics.

Off-Nominal Event Characteristics: Phase of Flight, Expectancy and Event Location

Three characteristics of the off-nominal events were evaluated: Phase of flight, event expectancy, and event location. These main effects, and interactions among them, are described below. Event characteristics that were also moderated by the absence or presence of flight deck technologies will be described in the following section.

Phase of flight. An analysis of miss rate (that is, the rate that pilots failed to detect an off-nominal event) revealed that across all 26 studies in our analysis, the probability of missing an off-nominal event was highest during departures ($p_{\text{miss}} = .50$), followed by cruise ($p_{\text{miss}} = .47$), arrival/approach ($p_{\text{miss}} = .39$), and taxi ($p_{\text{miss}} = .20$; χ^2 (3) = 34.61, $p < .001$). The reader is cautioned in interpreting the departure miss rate, however, as this was comprised of only one study with eight pilots. These miss rates may reflect an expectancy effect as pilots tend to be more vigilant and aware of both the traffic environment and their aircraft status during the arrival and taxi phases than in the cruise and departure phases. They may also reflect a location effect as events during cruise tended to be located on the instrument panel, but during approach the event tended to be out-the-window (OTW).

Expectancy and event location. The effect of expectancy on pilot detection of off-nominal events was assessed by comparing the miss rate from the *first off-nominal event* a pilot experienced to that from all subsequent off-nominal events. As would be expected, the probability of missing the event was higher if it was the first event ($p_{\text{miss}} = 0.48$) than for subsequent off-nominal events ($p_{\text{miss}} = 0.29$; χ^2 (1) = 24.70 $p < 0.001$). This produced an **Unexpectancy Cost of 0.19**. Next, the off-nominal events across all available studies were classified as occurring either OTW or head-down in the cockpit. The probability of missing an event was lower when it was OTW (p_{miss} = 0.29) than when it was head down (p_{miss}= 0.39), $\chi^2(1) = 9.88$, $p < 0.01$, yielding a **Cockpit Location Cost of 0.10**. The analysis also yielded an interaction between event expectancy and location. There was a large unexpectancy cost when the off-nominal event was OTW (p_{miss} for first OTW event = 0.50; p_{miss} for subsequent OTW events = 0.23; χ^2 (1) = 39.86, $p < 0.01$; **OTW Unexpectancy Cost of 0.27**) but when the off-nominal event was within the cockpit, there was no difference in miss rate as a function of expectancy (p_{miss} = 0.41 for both). This could reflect that pilots bring their own knowledge of real-world expectancies to the HITL study since in actual operations the frequency, and therefore expectancy, of a head-down event is much greater than for OTW events. In other words, in the simulations, the first cockpit event, was not as truly surprising as the first OTW event.

Flight Deck Technology: HUDs, HITS, Datalink, and Graphical Route Displays

The analyses of pilots' event detection as a function of the presence of various advanced cockpit technologies was largely driven in a bottom-up fashion by the available literature. The technologies reflect a range of technologies that may be incorporated into future advanced cockpits. These include head-up displays (HUDs), highway-in-the-sky (HITS) displays, datalink, and graphical route presentations.

Head-up display (HUD). HUDs are used in current operations for approach and landing, and may be used in NextGen for surface operations and to support low-visibility operations. An analysis using six HITL studies evaluated whether the presence of a Head-up Display (HUD) affected the probability of detecting an off-nominal event (regardless of event location). The probability of missing an event was higher when the pilots were flying with a HUD (p_{miss} = 0.39) than without (p_{miss} = 0.31), $\chi^2(1) = 4.13$, $p<.05$. This produced a **HUD Cost of 0.08**. This HUD effect was modified by the location of the off-nominal event in a manner that reflects the classic Fischer, Haines, and Price (1980) finding that the HUD particularly obscures unexpected OTW events (See also Fadden, Wickens, & Ververs, 1999). When the off-nominal event occurred OTW, the probability of missing the event was greater when pilots were flying with the HUD (p_{miss} with HUD = 0.36), than without (p_{miss} without HUD = 0.27; χ^2 (1) = 4.63, $p < .05$) producing an **OTW HUD Cost of 0.09**. But, if the event occurred head-down in the cockpit, the probability of missing the event was lower (though not significantly) when flying with the HUD (p_{miss} with HUD = .46) than without (p_{miss} without HUD = .51; $\chi^2(1) = .40$, $p = .53$; non-significant **Cockpit Location HUD Benefit = .05**[2]).

Highway-in-the-sky (HITS). A HITS display integrates lateral, vertical, and longitudinal information of the flight path into a perspective path through the air (Wickens & Alexander, 2009). While it may be presented either on a HUD or head-down display, it was presented head-down in all ten studies used in our analysis. The probability of missing an event (all events were OTW) when flying with a HITS display was higher (p_{miss} = 0.45) than when flying without the HITS display (p_{miss} = .22; $\chi^2(1) = 31.03$, $p < .001$). This produced a **HITS Cost of 0.23**, presumably due to the fact that the head-down HITS reduced eyes-out time and induced cognitive tunneling (Fadden, Ververs, & Wickens, 2001; Wickens & Alexander, 2009). The HITS cost remained when we consider only the first, truly surprising OTW event (p_{miss} with HITS = .55; p_{miss} without HITS = .33; χ^2 (1) = 7.01, $p <.01$; **HITS Cost for Truly Surprising OTW Events = .22**).

Datalink. It is expected that NextGen will include datalink communications between pilots and ATC (JPDO, 2007). A great deal of research has evaluated a range of datalink issues such as pilot workload, situation awareness, and heads-down time (e.g., Smith, Polson, Brown, & Moses, 2001). Four studies were identified that compared pilots' ability to detect an off-nominal event (all events were ATC clearance errors) when presented via datalink and/or voice. The probability that a pilot missed a clearance error was more than twice as high when the clearance was presented via datalink alone (p_{miss} = 0.69) than by voice alone (p_{miss} = 0.33) and voice with datalink together (p_{miss} = 0.38; $\chi^2(2)$= 25.73, $p < 0.001$). There was no significant difference in the probability of missing the error between voice and voice with datalink ($\chi^2(1) = 0.12$, $p = 0.72$), so the presence of voice appears to be a buffer, or error-trapping agent, against clearance comprehension errors (see Hooey, Foyle, & Andre, 2001). (The reader is cautioned that the data for voice-only clearance errors are limited to 18 subjects from a single study). A comparison of the voice with datalink and datalink-only conditions yielded a **Datalink-only Cost of 0.31.**

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[2] Costs and Benefits are provided, even when non-significant, as they are expected to be useful for populating HPMs, the intended purpose of these analyses.

Next, a distinction was made between those clearances that were inappropriate (such as a clearance to turn onto an occupied taxiway creating a nose-to-nose conflict) and those that were impossible (such as a clearance to climb to an altitude below the current altitude). Inappropriate clearances tend to be subtle distinctions that require greater cognitive processing whereas impossible clearances tend to be more salient and obvious. In looking first at inappropriate clearances, the probability of missing a clearance error was much higher when the inappropriate clearance was issued via datalink ($p_{\text{miss}} = 0.85$) than when issued by both datalink and voice ($p_{\text{miss}} = 0.5$; $\chi^2(1) = 12.27$, $p < 0.001$; **Datalink Cost for inappropriate clearances = 0.35**), however, the datalink cost was not significant for impossible clearance errors (p_{miss} with datalink = 0.54; p_{miss} with voice and datalink = 0.44; $p>0.1$; non-significant **Datalink cost for impossible clearances = 0.1.** Therefore, the pilots caught the more salient impossible errors equally often with or without datalink but were hindered by datalink in detecting the less salient inappropriate errors. This could reflect a criticality difference between the two error types, however there were insufficient data to test this hypothesis.

Graphical routes. Displays that graphically present route information include electronic moving maps for airport surface operations (Hooey, Foyle, & Andre, 2001) or flight procedure rehearsal tools (Arthur, et al., 2004), among others. Four studies were identified that met the meta-analysis criteria and evaluated the effect of graphical displays on pilot detection of off-nominal events. Surprisingly, there was no main effect of the presence of a graphical rendition of the clearance on error detection rates. When the clearance (regardless of delivery method) was accompanied by a graphical presentation within the cockpit, the probability of missing the clearance error was 0.64 as compared to 0.65 when no graphical depiction accompanied the clearance ($\chi^2(1) = 0.03$, $p = 0.87$; non-significant **Graphical Route Benefit = 0.01**). However, for events in which the clearance was merely inappropriate, but not impossible, it appears as if the graphical presentation did improve event detection (p_{miss} with graphical route = 0.75; p_{miss} without graphical route = 0.86; $\chi^2(1)=3.6$, $p = 0.057$; **Graphical Route Benefit for Inappropriate Clearance Errors = 0.11**). The graphical route benefit was not observed for impossible clearances, with the trend in the opposite direction (p_{miss} with graphical route = 0.56; p_{miss} without graphical route = 0.49; $p > 0.1$; non-significant **Graphical Route Cost for Impossible Clearance Errors = 0.07).**

Discussion

This meta-analysis characterized pilots' miss rate for off-nominal events as a function of expectancy, event location, and the presence or absence of various advanced flight deck technologies. It was observed that the miss rate data produced several plausible and significant effects including:

- An overall miss rate of .32
- An unexpectancy cost for first, truly surprising events, especially OTW events
- A cockpit location cost
- A HUD cost, especially for OTW events
- A HITS cost for OTW events
- A datalink cost, especially for inappropriate clearances
- A benefit of graphical routes for inappropriate clearances

While the existence of these and other effects confirms prior work, most critically the current analyses provided robust, stable estimates of their effect size in real-world meaningful units.

An important finding was that the presence of the advanced technologies either hindered off-nominal event detection as was the case for HUDs, HITS, and Datalink, or failed to show a significant benefit for event detection as was expected from the graphical routes. These results may reflect cognitive tunneling effects especially for the HUD and HITS technologies (Fadden, Ververs, & Wickens, 2001; Wickens & Alexander, 2009) and general complacency effects as has been well documented in Parasuraman, Molloy & Singh (1993). This raises a concern for NextGen flight deck design and points to the need for careful consideration of both nominal and off-nominal conditions in the design and evaluation of NextGen technologies and operations. The results of this parameter meta-analysis reveal insights for the development of countermeasures in terms of training, procedures, and on-board alerts and warnings to mitigate the failure to detect off-nominal events. For example, it was seen that when pilots have some forewarning that an event could happen in the simulation studies, the miss rate dropped by 19%. Looking just at OTW events, the miss rate was 27% if pilots were forewarned of the possibility of the event. This suggests that training to remind pilots of the possibility of various events (such as runway incursion 'hot spots' or areas prone to bird strikes), or displays that indicate traffic or weather in the area, even if they are accompanied with high amounts of uncertainty, may reduce the miss rate. The finding that HUD and HITS both reduced event detection could suggest the need to mandate that airlines adopt procedures specifying that when one pilot uses the HUD or HITS, the other pilot must be eyes-out. Finally, the finding that datalink inhibited event detection, especially for inappropriate clearances, is of concern as these clearance errors are the most difficult for both pilots and automation to detect. This result may reinforce procedures that the pilots read the datalink out loud within the cockpit to maximize error detection.

Limitations and Opportunities for Future Research

Each study included in this parameter meta-analysis was conducted with independent research objectives and therefore all differed on important factors relating to the events, flight scenarios, and measurement techniques. One inevitable consequence of any meta-analysis is that the diverse studies may differ from each other on variables other than those used for classification. In some cases this pooling may cause an increase in variance within a category, diluting the strength of an effect. In other cases, it may cause a confound (e.g., studies with a HUD used, on average, pilots with more experience than those without). While it might in some cases have been possible to create an additional category of "experience" (assuming adequate reporting of this variable by the independent researchers) the danger of creating progressively more classification dimensions is that the number of observations within each cell becomes so small that statistical comparisons are challenged. A second limitation is that many of the HITL studies included in the analyses employed a single-pilot, general aviation crew as test subjects. It is possible that two pairs of eyes in the commercial cockpit could reveal a different (presumably lower) miss rate. Finally, it is noted that all data were drawn from HITL simulations and there is always the concern that pilot performance in simulation does not mirror pilot performance in actual operations (see Newman & Anderson, 1994). There is a real need for continued off-nominal event research to further populate the existing off-nominal database to increase the robustness and validity of these findings.

Conclusion

By pooling data across disparate HITL studies, many of which lacked statistical power to draw conclusions and generalize findings when considered individually, we identified several factors that have a robust influence on human performance in off-nominal environments. Three of the variables reported here (Expectancy, Event Location, and HITS) were used to validate a model of visual attention (N-SEEV; Wickens et al., 2009) which then was used to predict pilots responses to off-nominal events in NextGen environments (see Gore et al., 2009). Following HPM efforts will use a larger set of these meta-analysis findings to populate HPMs with valid estimates of pilot performance to estimate response time and accuracy to off-nominal events in the Next Generation Air Space System and to evaluate proposed mitigating solutions.

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Acknowledgements

This research was supported by a NASA Research Announcement awarded to San Jose State University Research Foundation by NASA's Airspace Super Density Operations Project (NRA # NNX08AE87A; COTR Dr. David Foyle).