IS RHO THE KEY TO HAZARDOUS WEATHER AVOIDANCE?

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Current in-cockpit looping Next-Generation Radar (NEXRAD) is inadequate to maintain safe (20 nm) aircraft separation from heavy weather (> 40 dBZ reflectivity). This assertion is supported by mathematical information analysis and an empirical study (Knecht, 2016), as well as numerous previous empirical studies. The current work revisits the ecological analysis by examining the putative affordance ρ (rho) specifying when weather-avoidance maneuver should begin, as suggested by General Tau Theory (Lee, 2009). With "gap" defined as the distance between the on-screen aircraft icon and the weather hazard, ρ is specified by the ratio *((dg/dt)/g)(t)*, the instantaneous gap contraction rate divided by the instantaneous gap size. In current looping NEXRAD, ρ clearly does not reach perceptible threshold until too late to facilitate 20 nm separation from hazard. The addition of a range ring plus future-predicted weather and aircraft position could remedy this deficiency, enabling safe, efficient navigation around heavy weather.

Introduction

Background

Adverse weather remains a perennial challenge for all aviation, particularly for the smaller aircraft of general aviation (GA) and, therefore, a high priority for the U.S. Federal Aviation Administration (FAA). One important focus area involves pilot interpretation and use of color-coded weather-risk displays. In the U.S., the best known of these is the National Weather Service (NWS) NEXRAD. GA pilots are now being offered NEXRAD capability in the cockpit, for instance via XM satellite radio, and on handheld devices like tablet computers and smartphones. From a human-factors perspective, NEXRAD is effectively a *risk-proxy gradient*—a graphical representation of relative weather-related risk. Such gradients contain important perceptual information pilots can use to make hazard-avoidance decisions (Knecht & Frazier, 2015a; Wiggins, Azar, & Loveday, 2012)—particularly, how close their flight plan may take them to hazardous weather.

Normally, NEXRAD images are updated only about once every five minutes. But, rapid playback of about an hour's worth of individual frames is enough to create a time-lapse movie of precipitation. Repeating ("looping") such a movie conveys a strong sense of apparent motion (Wertheimer, 1912), enhancing the perception of where a storm is heading.

Nevertheless, looping NEXRAD ultimately shows a movie of where precipitation *used to be*. At issue is whether that information can be used to predict where both the aircraft and hazardous weather *will be* in the near future.

We know that pilots can estimate closest point of approach to storms on NEXRAD to a degree. Psychophysical studies by Bootsma & Oudejans (1993) have mathematically verified both the presence of detectable information in "an object moving toward a designated position," as well as the ability of observers to detect that information. Nonetheless, in virtually every aviation-related NEXRAD study to date (all *in simulo*), a substantial proportion of pilots seemed to overestimate closest point of approach (CPA), meaning they overestimated eventual minimum separation from heavy weather, and ended up approaching too closely (ATSC, 2013; Beringer & Ball, 2004; Burgess & Thomas, 2004; Hua, 2014; Knecht, 2016; Knecht & Frazier, 2015a,b; Lemos & Chamberlain, 2004; Novacek, Burgess, Heck, & Stokes, 2001; Wu, Duong, Koteskey, & Johnson, 2011; Wu, Gooding, Shelley, Duong, & Johnson, 2012; Wu, Luna, & Johnson, 2013; Yuchnovicz, Novacek, Burgess, Heck, & Stokes, 2001). In no study did all pilots consistently maintain the 20 nm separation from heavy weather advised in FAA AC 00-24-C (Table 1, FAA, 2013, p. 10, Sec 9c)

In previous investigation (Knecht, 2016) we took a theory-based look at the visual information present in looping NEXRAD. The current work revisits that investigation and suggests possible avenues of further research. The approach is that of *ecological psychology* (Gibson, 1979), *neurocomputation* (Marr, 1982), and *ecological interface design* (Dinadis & Vicente, 1999, Borst, Flach, & Ellerbroek, 2015), namely examination of the visual elements of a scene's "ecology" to determine *affordances*—information capable of "affording" completion of a given task in the sense of providing, supplying, facilitating, or enabling it in a way mathematically describable and computationally plausible by structures of neurons. Of particular concern to us in this discussion are the visual affordances in a NEXRAD display that would allow keeping an aircraft icon 20 scale miles away from “heavy” weather.

Summary of Key Findings to Date

The search for task-relevant information. Figure 1a represents an idealized map display of an aircraft moving NW in straight-line motion for 35 minutes with constant velocity $V_{aircraft}$ = 120 kt. Imagine a single point on the nose of the aircraft icon approaching a single designated point on the edge of a storm that does not change shape, but moves ENE in straight-line motion with constant velocity V_{storm} = 30 kt.

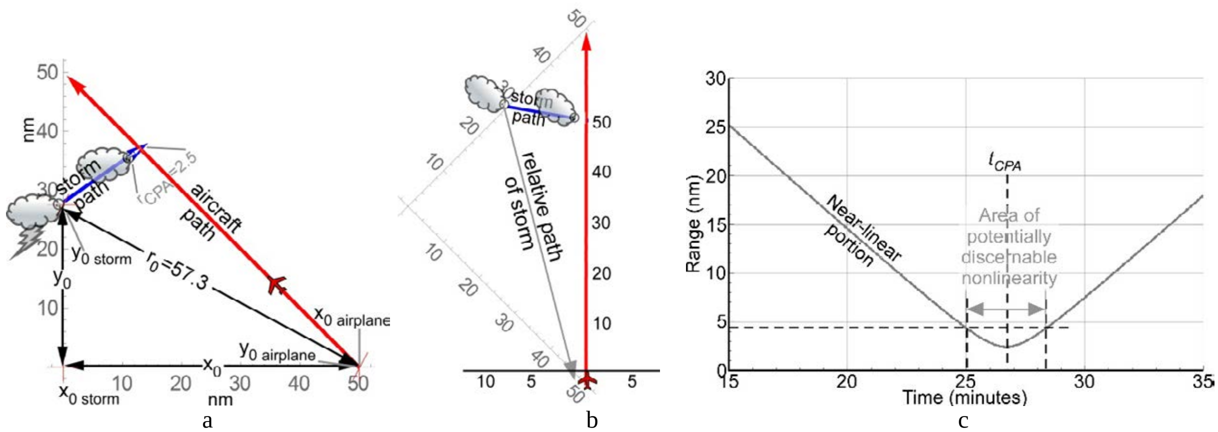


Figure 1, a) Cartesian geometry of a “pass-by” situation with 57.3 nm initial separation and CPA = 2.5 nm, b) the same situation rotated (45° clockwise), now depicting an aircraft-centered, moving-map display showing the storm’s resulting relative motion (the logic of Eqs. 1 and 2 (below) is based on 1b), c) the gap function plotted over time produces a “rounded-V” shape having zero slope at time-of-CPA (t_{CPA}).

Avoiding a single point on such a storm’s edge is arguably the simplest possible case of “weather avoidance.” In reality, there would be many such points to consider along that edge, but we can consider just one because their mathematical logic will be similar.

Figure 1b shows the same weather situation, but transformed into the perspective of *relative* motion (Lenart, 1983) such as you would see in a *moving-map* format, centered on the aircraft, with the world rotated (here, 45° clockwise) to show the aircraft path headed straight up. The aircraft appears to stand still while objects around it move.

For a looping NEXRAD display without future-projection of weather, Figure 1c shows Figure 1a’s *gap function*—the parametric (time-based) equation describing the instantaneous range r_t, or gap, between the tip of the aircraft icon and that single, moving point on the storm at time *t:*

$$r_t = \sqrt{(x_0 + v_x t)^2 + (y_0 + v_y t)^2} \tag{1}$$

where x_0 and y_0 are initial relative separation distances (e.g., $x_0 = x_{0\,aircraft} - x_{0\,storm}$), and v_x and v_y are relative-velocity components (e.g., $v_x = v_{x\,aircraft} - v_{x\,storm}$), all of which can be estimated by comparing at least two views of the situation, separated by a known amount of time.

Solving Equation 1 for slope $d_r/d_t=0$ gives us CPA—the task-relevant information we need (see Knecht, Smith, & Murphy (2000), Appendix 1 for derivation). This shows that—at least in the absolute simplest case—looping NEXRAD theoretically contains sufficient information for pilots to estimate how close they will approach a storm boundary.

$$CPA = \sqrt{\frac{(x_0 v_y - y_0 v_x)^2}{(v_x^2 + v_y^2)}} \tag{2}$$

Implausible vs. plausible solutions. We have retinal structures sensitive to position, various sizes of gap, angular orientation (Hubel, 1988), and motion (van Santen & Sperling, 1985). So, it may be plausible to detect the individual components of Equation 2. However, it is not plausible to imagine noisy neurons accurately executing all the delicate mathematical operations in the exact fashion specified by Equation 2.

We therefore look for a “hack”—some clever feature of the situation that might sidestep complicated computation, allowing what Gibson called *direct perception*. For instance, pilots have a hack to directly perceive if a distant airplane will collide with theirs. They just look out the window. If the relative position of the approaching aircraft on the windscreen never changes, but it keeps getting bigger and bigger—that represents an eventual collision (Bootsma & Oudejans, 1993).

The challenge is finding such a hack. Examining Figure 1c, we might, for instance, monitor the V-shaped gap function in non-future-projected looping NEXRAD to look for a sudden *change* in its slope (i.e., the second derivative). However, that approach seems implausible. As Figure 1c clearly shows, a “V” gives nearly no change-in-slope information until the time $t \approx 25$ minutes, where the aircraft is practically at CPA, and already dangerously close to the storm.

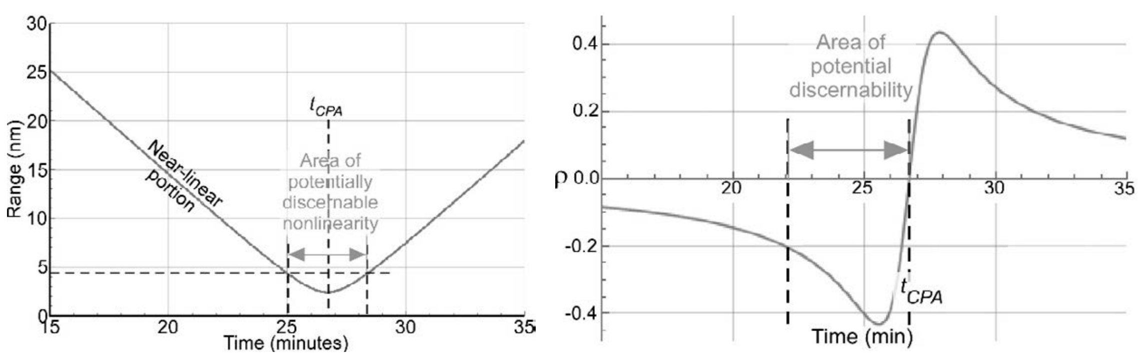
Ecological Enhancements for a Better Display

Rho as a potential cue to triggering avoidance maneuvering. Lee (2014) has considered ecological situations analogous to ours, namely ones where a viewer sees a gap changing size over time. The *way* the gap changes can serve as a trigger stimulus for actions such as an avoidance maneuver. The information that forms this potential trigger stimulus is called ρ (rho), and is defined (Eq. 3) as the *relative rate of change of the size of the gap.*

$$\rho_t = \frac{dg/dt}{g_t} = \frac{\text{instantaneous change in gap size}}{\text{instantaneous gap size}} = \frac{\text{slope of the gap function at time } t}{\text{size of the gap at time } t} \qquad (3)$$

Readers may recognize ρ as essentially the inverse of τ (tau, that is *time-to-contact*), which is the basis of General Tau Theory (Lee, 2009). Regardless, the concept itself is simple enough. Given, say, a shrinking gap between an onscreen aircraft icon and a storm cell, the faster the gap is shrinking (bigger numerator)—or the smaller the gap itself is (smaller denominator)—the bigger ρ will be. The ratio forming ρ changes over time, and Bootsma & Oudejans (1993) suggest mathematical approximations that could be plausibly implemented by neurons without the need for implausibly extensive or delicate computation.

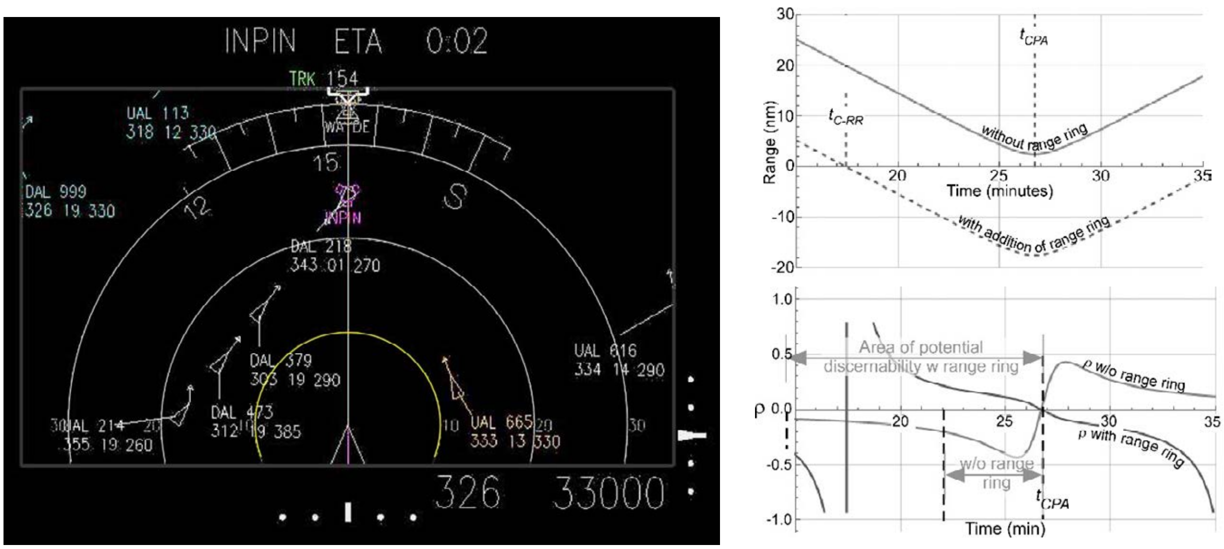
Figure 2a below is merely 1c repeated for convenience. Figure 2b shows how, in an onscreen conflict situation such as looping NEXRAD, the value of ρ would grow large enough to exceed a fixed threshold and trigger a neural circuit sufficiently far ahead of time to cover reaction and maneuver times. And, because any gain made in early alert translates directly into *available maneuver time*, ρ might constitute a key element in hazard avoidance.



a b

Figure 2a. The gap function of Fig. 1c, b) the time-evolution of ρ. Note that the threshold for earliest-time-of-discernability could be lower than that of mere slope change detection (Fig. 2b, $t \approx 22$ minutes, about 3 minutes sooner than in Fig. 1c).

Addition of a range ring to the display. The addition of a range ring around the aircraft icon (Fig. 3a) should theoretically add even more benefit to a looping display.



a b

Figure 3a. A cockpit multifunction display showing range rings centered around the aircraft icon, b, upper) The gap function with and without a 20-nm range ring, b, lower) time-evolution of ρ, and areas of potential discernability, with and without 20-nm range ring.

Figure 3b (upper) shows how a 20-nm range ring changes the gap function by effectively decreasing the instantaneous distance-to-hazard by 20 nm. If "Plan A" for hazard avoidance is based on perception of ρ in a looping display, then Figure 3b (lower) shows a marked decreased in earliest time-of-potential-discernability, from about 22 minutes without the range ring down to less than 15 minutes with it. In other words, having a range ring gains could provide 7 minutes additional maneuver time in this particular case.

Moreover, Figure 3a (upper) shows that the range ring itself will ultimately directly contact the edge of the hazard at time $t_{C\text{-}RR} \approx 17.4$ minutes, while the aircraft is still 20 nm distant. This constitutes a "Plan B" backup alert for even the least-attentive pilot.

Addition of a range ring *and* future-projected weather. Obviously, accurate estimation of the positions of both the aircraft icon and weather—even with as short as 30 minutes lookahead—would be a major step forward in tactical weather avoidance. This would eliminate having to depend on perception of an early-warning stimulus such as ρ. The display could either be looped, or simply "time-scrolled" ahead to see if the range ring itself contacted any hazard.

At issue, of course, is the accuracy of the convective weather forecasts themselves. Conversations with Keith Brewster (personal communication, July 30, 2015), Associate Director of the Center for Analysis and Prediction of Storms (CAPS) lead us to believe that 45 minutes lookahead appears feasible with current supercomputers running 3-km-resolution storm modeling. About 15 minutes of that lookahead would be needed to compensate for processing and data-broadcasting time, leaving the net 30-minute gain envisioned as necessary.

Conclusions

The Importance of Ecological Information Design

As human factors researchers, we need to be able to determine how task-critical in-formation from technological systems is detected by the user (Vicente, 1999). If we begin with the information present in the stimulus, we can then imagine how that information could be detected or derived by simple neural circuits. If these exist, then there may be the possibility for accurate, efficient, effortless Gibsonian direct perception, and the technology may function efficiently with little modification.

On the other hand, if we can logically show that either no easily detectible task-critical information exists in the stimulus, or no such simple neural detector of that information is plausible, then we can deduce that perception and/or cognition must be constructed. Constructed cognition is almost by definition less efficient, more error-prone, and is therefore an opportunity for augmented perception and augmented cognition, such as the theory and method of ecological interface design, which seeks to “make visible the invisible” (Vicente & Rasmussen, 1990.

Naturally, no cockpit display, no matter how advanced, can guarantee 100% freedom from weather hazard. Human factors issues always remain (e.g. “get-home-it is,” fatigue, training issues, and so forth). Nonetheless, we feel compelled to support all efforts regarding the art and science of ecological interface design. To analyze the information available in the visual stimulus, to discern which tasks rely on hard-to-derive information, and to find creative ways of making visible the invisible are things clearly worth our effort. Ecologically enhanced displays have already shown considerable success in tactical aircraft collision avoidance (Ellerbroek, Visser, van Dam, & van Paassen, 2011; van Dam, Mulder, & van Paassen, 2008). Since weather is more or less a “large flying object,” similar ecological approaches could, and should, be developed and tested.

Future research

Future research should center, first, on testing “the rho hypothesis” in a simplified psychophysical setting, for instance testing human ability to detect impending onscreen collisions between small moving dots. If psychophysical research confirms ρ as a likely stimulus capable of triggering avoidance maneuvering, then it would make sense to pursue the investigation, examining looping-NEXRAD displays with range rings and, ultimately, with range rings and future-projected storm displays.

Acknowledgements

This study was sponsored by FAA ANG-C61, Weather Technology in the Cockpit Program, and supported through the FAA NextGen Human Factors Division, ANG-C1.

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