Two-Tail Non-Linear Moving Tape Displays

by

Dave English

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Graduate Supervisory Committee:

Russell J. Branaghan, Chair
Nancy J. Cooke
Christopher A. Sanchez

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ABSTRACT

Fixed-pointer moving-scale tape displays are a compact way to present wide range dynamic data, and are commonly employed in aircraft and spacecraft to display the primary parameters of airspeed, altitude and heading. A limitation of the moving tape format is its inability to natively display off scale target, reference or 'bug' values. The hypothesis tested was that a non-linear fisheye presentation (made possible by modern display technology) would maintain the essential functionality and compactness of existing moving tape displays while increasing situational awareness by ecologically displaying a wider set of reference values.

Experimentation showed that the speed and accuracy of reading the center system value was not significantly changed with two types of expanded range displays. The limited situational awareness tests did not show a significant improvement with the new displays, but since no functionality was degraded further testing of expanded range displays may be productive.

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This work was started under the expert eye of my original advisor Roger Schvaneveldt, now professor emeritus. It was also aided by conversations with Rob Gray, now at the University of Birmingham, England.

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INTRODUCTION

Instruments that accurately display a wide range of values have to be themselves very large, or if this is not physically possible then the resolution of the display has to be reduced, and/or the displayed range has to be reduced, and/or secondary vernier scales used. A middle-school science experiment for measuring atmospheric pressure illustrates reduction in resolution: a simple barometer made of water in a plastic pipe will stand several stories high outside the science building whereas one made with mercury in a glass tube will fit in a room due to the mercury's increased density. The resolution of the display is reduced, but the mercury device is much more convenient to transport and read. Mercury barometers were the first flight instruments, carried aloft in balloons at the end of the 18th century by early aeronauts (Chorley, 1979). Even smaller than a mercury barometer is a single digital readout from a pressure transducer, as now the entire display can be just a few glowing digits. A single digital number can be quickly and precisely perceived (Hosman & Mulder, 1997), but limitations with single readouts include poorly displaying dynamically changing data (Sanders & McCormick, 1993; Rolfe, 1965), problems with making quick qualitative estimations (or 'check readings') (Sanders & McCormick, 1993; Harris, 2004), and not allowing for easy comparison with reference values (whereas, for example, yesterday's air pressure can be easily marked on a glass barometer tube using a grease pencil or a system limitation for an automobile tachometer can be marked with a red line).

A partial solution to the problem of conveniently displaying data of this type is to wrap the strip display into a more compact shape, as seen in aneroid barometers employing round dials. To increase precision in dial displays, a second needle can be added that shows more precise values within a restricted range indicated by the primary needle; examples of which are the dial caliper and the minute hand on a traditional round clock face. A third needle for more precision can even be added. The seconds hand on a traditional round clock face allows an efficient display of hours, minutes and seconds with a range of 12 hours – or over 43,000 seconds. Although the round clock face is an elegant design, it has long been known there are human factors challenges to reading analogue clocks (Grether, 1948). Clock faces and barometers came together when the multiple needle concept was used in the two and then three needle altimeter (figure 1).

Figure 1: One, two and three needle altimeters, reproduced from Nicklas, 1958

Altimeters have to display to a resolution of less than 10 feet with a range of approximately 45,000 feet for civil jet aircraft, over 60,000 feet in military applications and an even greater number for space vehicles. The three needle design does accomplish this. However, with the additional demands above that of a time clock (i.e. a display value that that moves in both directions at varying rates), coupled with its vital importance to flight safety, the three needle altimeter quickly became the subject of much aeronautical concern and research. In one early study, multiple-pointer and long-scale instruments were associated with the greatest number of serious cases of instrument misreading (Fitts & Jones, 1947). In another article difficulties in reading the altimeter and airspeed indicator were described by almost half the pilots interviewed (Fitts, Psychology and aircraft design: A study of factors pertaining to safety, 1947). Ten years later, a study of Indian Air Force pilots and navigators found over 30% of their three-needle altimeter readings were wrong (Adiseshiah & Prakash Rao, 1957). Airline pilot and human factors researcher David Beaty later called the three-needle altimeter, "the most notorious deceiver of all aircraft instruments" (Beaty, 1991, p. 71). It has been directly implicated in several fatal airliner accidents, including the 1958 crash of a BOAC Bristol Britannia:

> The accident was the result of the aircraft being flown into ground obscured by fog. This was caused by a failure on the part of both the captain and the first officer to establish the altitude of the aircraft before and during the final descent. . . . The height presentation afforded by the type of three-pointer altimeter fitted to the subject aircraft was such that a higher degree of attention was required to interpret it accurately than is desirable in so vital an instrument. (ICAO, 1962, p. 47)

The crash of a BEA Vickers Viscount in the same year was officially found to be, "caused by the captain flying the aircraft into the ground during the descent to Prestwick after misreading the altimeter by 10000ft" (ICAO, 1959, p. 132). Don Harris has concluded that, "the altimeter is probably the single instrument that has been responsible for the deaths of more pilots than any other. It has also probably attracted almost as much research attention as the [Attitude Indicator]” (Harris, 2004, p. 86).

Walter Grether (1949) performed seminal experiments with nine types of displays testing the speed and accuracy of their presentations, and his clear results are reproduced here as figure 2.

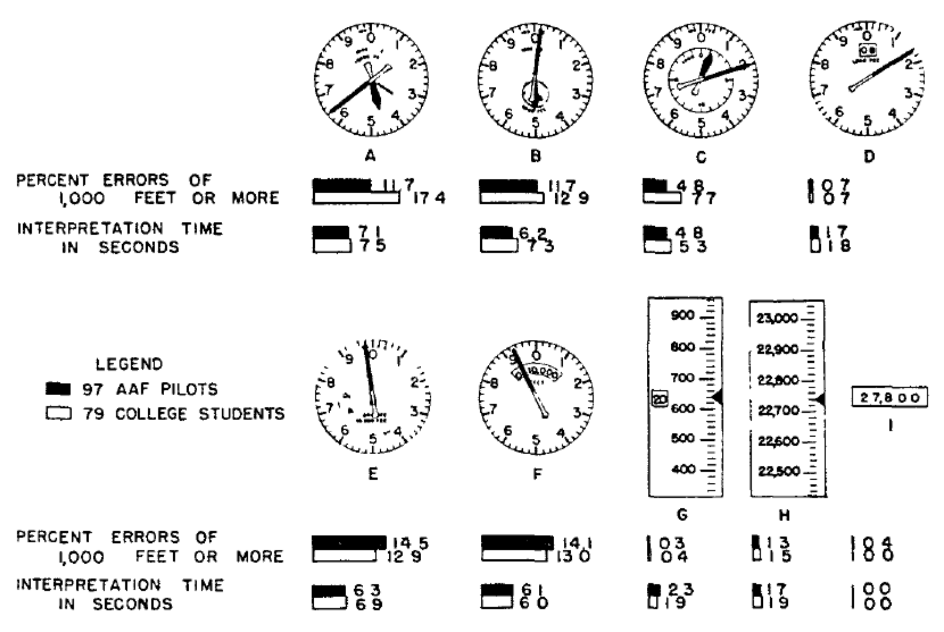

Figure 2: Performance of various altimeter designs, reproduced from Grether, 1949

It is seen that the dual counter drum with single pointer design ‘D’ was superior to all needle systems in terms of speed and accuracy for both trained Army Air Force pilots and novice college students. This design was subsequently used in high-quality mechanical altimeter displays. The experiment also included two interesting conceptual designs:

> Altimeter designs G and H are similar in that they simulate a scale moving vertically behind a window. An instrument following design G could use either an endless tape or drum to present the moving scale, with a counter to indicate multiples of 1000 feet. An instrument using design H would require a very long tape with a scale covering the desired altitude range. (Grether, 1949, p. 365).

Both these moving tape concepts tested very well for speed and accuracy, presenting the required resolution and sense of temporal qualitative movement by a employing a moving linear tape and restricting the displayed range. Moving scales with fixed pointers do however have the considerable disadvantage when compared to a fixed scale and moving pointer that can display the whole range, as a quick glance will not yield an approximate picture of system state, see figure 3 for clock face examples.

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Figure 3: Wristwatches With Fixed Pointers and Moving Dials

Ten years after the Grether study, the USAF has a working model of the moving tape display constructed using 16-mm movie film. Testing in a Link simulator found the tape display to be workable, but pointers resulted in a superior flight performance. Further experimentation with expanded scales and more training was recommended (Mengelkoch & Houston, 1958). In 1959 the Martin Company did extensive simulator testing of vertical tape instruments, with mixed results but predicting with design improvements that they would become valuable assets in the cockpit (Mengelkock, 1959). For a review of the primary research into vertical instruments see Kearns and Warren, 1962. In 1959 the Bulova Watch Company introduced a servo motor driven continuous tape altimeter for civil aircraft (figure 4) that looks a lot like design H. The new tape altimeter was claimed in company advertisements to, “cut reading time in half and virtually eliminate errors,” when compared to the rotary altimeters then in use (Altimeter is easy to read, 1959).

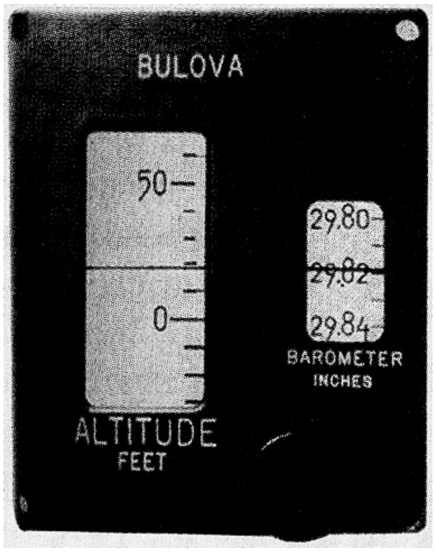


Figure 4: Bulova tape altimeter, reproduced from “Altimeter is easy to read,” 1959

The altimeter is not the only flight instrument to suffer from having to display a wide range. While early aircraft had fairly limited top speeds, with bigger engines and better aerodynamic designs came the problem of displaying a wider range of airspeeds (see Chorley, 1976; Lovesay, 1977; Nicklas, 1958, for reviews of many early flight instruments). Though not employing two or three needles like the altimeter, by the 1930's airspeed indicators had needles that swept more than 360 degrees of arc (figure 5).

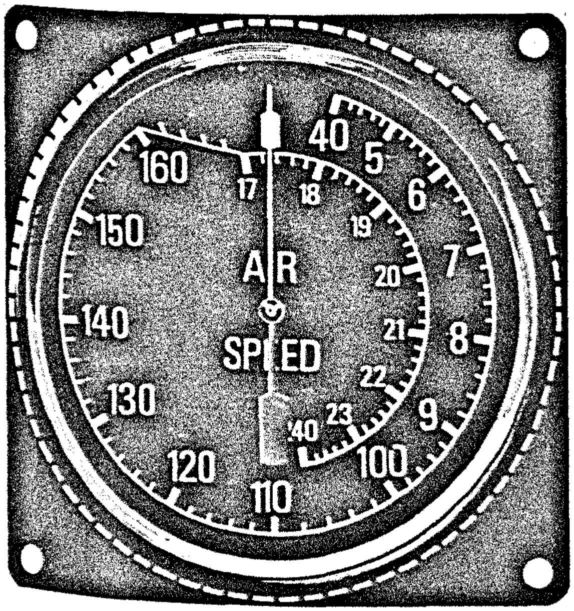


Figure 5: 1930's Airspeed Indicator, reproduced from Chorley, 1976

Aircraft continued to fly faster and higher; and with a top speed of over Mach 2 and capable of altitudes high enough for Edwards' test pilots to earn their astronaut wings, the legendary rocket-powered X-15 exemplifies the problem of increased instrument ranges. NASA conducted simulator experiments with X-15 cockpits equipped with either conventional needle instruments or a vertical-scale fixed-index (ACDS) instrument suite with six tapes and found that, "missions can be carried out as accurately and successfully with the ACDS panel as with the 'standard' model" (Lytton, 1967, p. 12). It was noted that experienced pilots were able to "garner a great deal of information from pointer rates and positions without having to ‘read’ parametric values,” (Lytton, 1967, p. 4) but more precision was expected with longer use of the tape displays due to their considerable gain in display sensitivity (one instrument had 40 inches of tape wound behind the window).

A problem with moving tape/fixed pointer displays is possible confusion caused by mixing this format of presentation with fixed tape/moving pointer displays in the same cockpit (known as the principle of the moving part, see Christensen, 1955; Roscoe, 1968; Johnson & Roscoe, 1972). However tape displays have been shown to be still readable when used with a variety of other instrument formats, and offer the practical advantage of a very compact form. An attempt to offer the best of both formats with a contra-moving pointer and scale presentation in both tape and circular formats was described but this format introduced its own complexities and has not seen service (Hopkin, 1966). Sanders and McCormick conclude that:

> Although fixed scales with moving pointers are generally preferred to moving scales with fixed pointers, the former do have their limitations, especially when the range of values is too great to be shown on the face of a relatively small scale. In such a case, certain moving-scale fixed-pointer designs . . . have the practical advantage of occupying a small panel space, since the scale can be wound around spools behind the panel face, with only the relevant potion of the scale exposed.” (Sanders & McCormick, 1993, pp. 135-136)

Electro-mechanical moving tape displays for airspeed and altitude entered service in transport category aircraft in 1964 with the introduction of the United States Air Force C141 aircraft, and were also deployed in the C5 fleet starting in

1969 (Hawkins, 1987). The tape-based “Integrated Flight Instrument System” (IFIS) was used in several U.S. front-line fighters (e.g. the F-105) developed in the 1960’s, as well as in the initial Space Shuttle cockpit (Lande, 1997). Following the IFIS, small (five-inch rather than eight-inch) tape displays for altimeter and airspeed indicators were evaluated by Tapia, Strock, and Intano (1975) at the USAF Instrument Flight Center. While the airspeed display was found to be adequate for future use, the altimeter display had some problems with the lack of range presented by the smaller size of tape. An indication of the limitations of tape displays in dynamic flight environments is seen in the mid-seventies when the USAF moved away from tape displays for heads down primary flight displays but retained their use for Head Up Display (HUD) symbology, seen for example in the F-15 (Lande, 1997). Air Force research presented in 1990 found HUD pointers better in basic flight performance than HUD tapes (Ercoline & Gillingham, 1990), and pointers rather than tapes are recommended by several sources for HUD applications (for an extensive review of HUD issues see Newman, 1995). A reminder that tape displays are also not optimum when a pointer can cover the required range was seen in testing of several formats for an F-16 vertical velocity indicator (Cone & Hassoun, 1991).

Civil aviation initially did not to follow the military’s use of moving tape presentations. The supersonic Concorde entered service in 1976 with circular moving needle instrumentation (Orlebar, 1986). The Boeing 757/767 entered service in 1982 pairing of cathode ray tubes (CRTs) for electronic attitude and horizontal situation indicators with electro-mechanical moving pointers for airspeed and altitude. The Airbus A320 introduced moving tapes with all flight instruments presented on two eight-inch CRTs (Coombs, 1990). The Boeing

Company conducted extensive research in the mid 1980's into vertical tape instruments, finding some concerns:

> They lacked relationships that were used extensively by pilots in performing flight tasks. This perception was strengthened by human factors research, which also concluded that, in general, moving scale displays are not as effective as moving pointer displays. The design constraints for the 747-400 PFD and the controversies that surrounded the vertical tape presentation provided a significant challenge to the display design engineers. (Konicke, 1988, p. 1)

Driven by explicit airline demands for the maintenance savings of CRTs over electromechanical pointers and the space requirements of matching the Airbus eight-inch screens, Boeing eventually chose vertical tapes for the 747-400. Tape displays for airspeed, altitude, and often heading have since become standard in electronic flight displays both civil and military aircraft (Long & Avino, 2001). Aircraft have tapes in both full-size displays (e.g. the Airbus Primary Flight Display (PFD), figure 6) and smaller standby or 'peanut' displays (e.g. the Airbus Integrated Standby Instrument System (ISIS)). The Airbus Primary Flight Display is a remarkably consistent presentation for tens of thousands of airline pilots, being introduced in 1987 with the A320, and then used essentially unchanged in the A318, A319, A321, A330 and A340 aircraft. And even though the A380 cockpit is supplemented by additional screens, the same presentation is still used as the primary flight display in the world's largest airliner (Vogel, 2009). There are more complex presentations in spacecraft, for example the seven tape Space Shuttle Multifunction Electronic Display System (MEDS), figure 7.

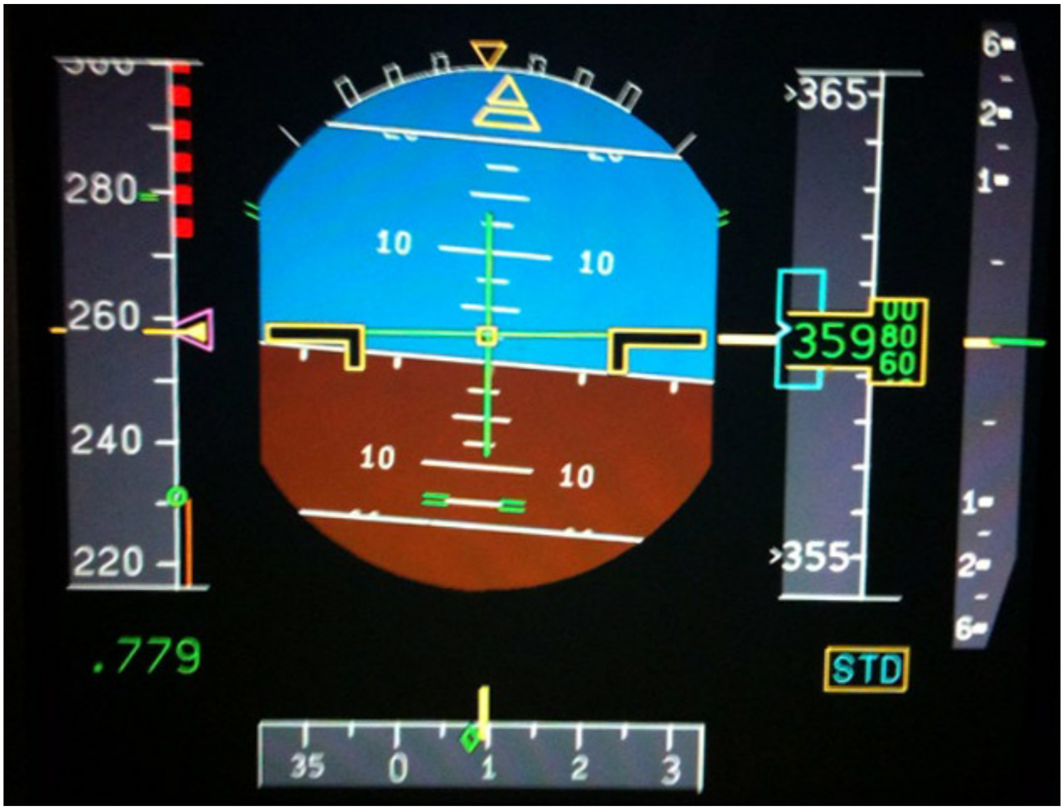


Figure 6: Airbus PFD

Figure 7: Space Shuttle MEDS, from Hayashi, Huemer, Renema, et al., 2005

Reviewing the Airbus PFD (figure 6) shows that there are markings on the tapes in addition to the unit scales, in the form of system parameter areas and pilot-set ‘bugs’. On the airspeed tape the green circle shows current computed best glide speed, and on altitude tape the cyan bug is the crew commanded altitude. On traditional mechanical airspeed dials colored bands indicate operational ranges for flight in different configurations of flaps/slats, average performance speeds, and airspeed limitations. Figure 8 shows such a traditional airspeed display for a light piston-powered aircraft with a white band for flight with flaps down, a green band for flight with flaps up, a yellow band for flight in smooth air, and a red maximum airspeed.

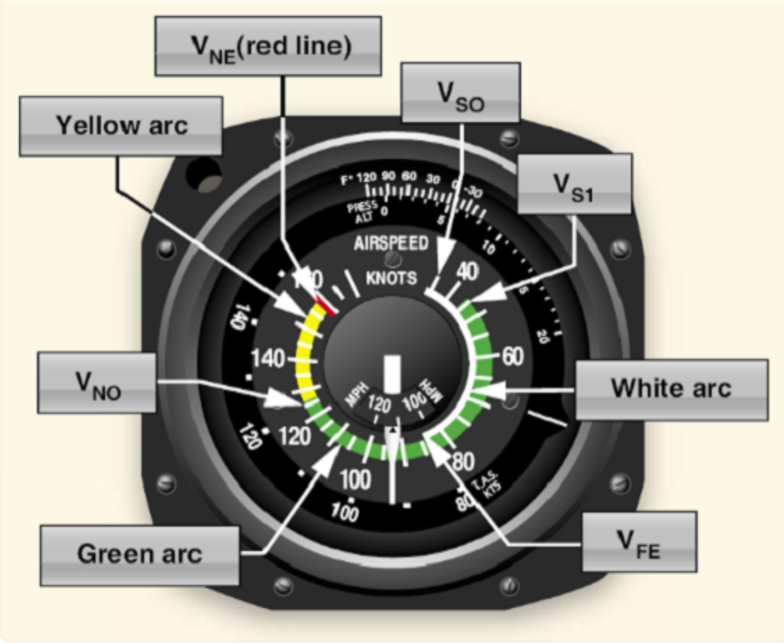


Figure 8: Round airspeed dial showing colored bands and limits, reproduced from FAA, 2008a

Higher performance aircraft have operational speeds that vary significantly with weight, center-of-gravity, density altitude, etc., so pilots will calculate the required speeds and set them on the display using movable ‘bugs’. Don Norman described this well:

> Speed bugs are plastic or metal tabs that can be moved over the airspeed indicator to mark critical settings. These are very valuable cognitive aids, for they transform the task performed by the pilot from memorization of critical air speeds to perceptual analysis. The pilots only have to glance at the airspeed and instead of doing a numerical comparison of the airspeed value with a figure in memory, they simply look to see whether the speed indicator is above or below the bug position. The speed bug is an excellent example of a cockpit aid. (Norman, 1991, p. 4)

More generally, the bands and bugs can be considered an example of ‘ecological interface design’ (Rasmussen & Vicente, 1989), directly displaying the process’ relational structure and so serving as an externalized mental model that will support knowledge-based processing. This was well described by Edwin Hutchins in his work as an ethnographer of cockpits and his expansion of the concept of what is a cognitive system:

> Airspeed bugs are involved in a distribution of cognitive labor across social space. The speed bug helps the solo pilot by simplifying the task of determining the relation of present airspeed to Vref, thereby reducing the amount of time required for the pilot’s eyes to be on the airspeed indicator. . . . The analog [airspeed indicator] display maps an abstract conceptual quantity, speed, onto an expanse of physical space. This mapping of conceptual structure onto physical space allows important conceptual operations to be defined in terms of simple perceptual

> procedures. Simple internal structure (the meanings of the regions on the dial face defined by the positions of the speed bugs) in interaction with simple and specialized external representations perform powerful computations. (Hutchins, How a cockpit remembers its speeds, 1995, pp. 285-6)

Modern aircraft with extensive digital avionics now calculate most of these speeds automatically and present bugs and graphical bands on tape displays that dynamically change, sometimes varying rapidly with, for example, g load, temperature or aircraft configuration. Figure 9 is a photograph of an Airbus A320 PFD during a descent out of FL 280 and the top of the airspeed tape shows the red-boxed overspeed limitation. Figure 10 is a photograph in the same plane taken about one minute later at approximately the same indicated airspeed that shows that the overspeed limitation has now moved off-scale (The A320-200 overspeed limitation in the clean configuration is the lower of 350 KIAS or 0.82 Mach; the increasing ambient air pressure due to decreasing altitude resulted in the indicated airspeed equivalent value of the Mach limitation becoming become larger, Hurt, 1965). Although the very important overspeed limitation is little more than 40 knots away from the current indicated airspeed, it is now no longer visible in figure 10. This limitation was noted by Mejdal, McCauley and Beringer (2001):

> Today's designers are less constrained by technology and do not have to present the entire scale or compass or airspeed dial. They now have the tempting option of presenting only the current value of the indicator, which can easily lead them into designing a poorer interface. (Mejdal, McCauley, & Beringer, 2001, p. 45)

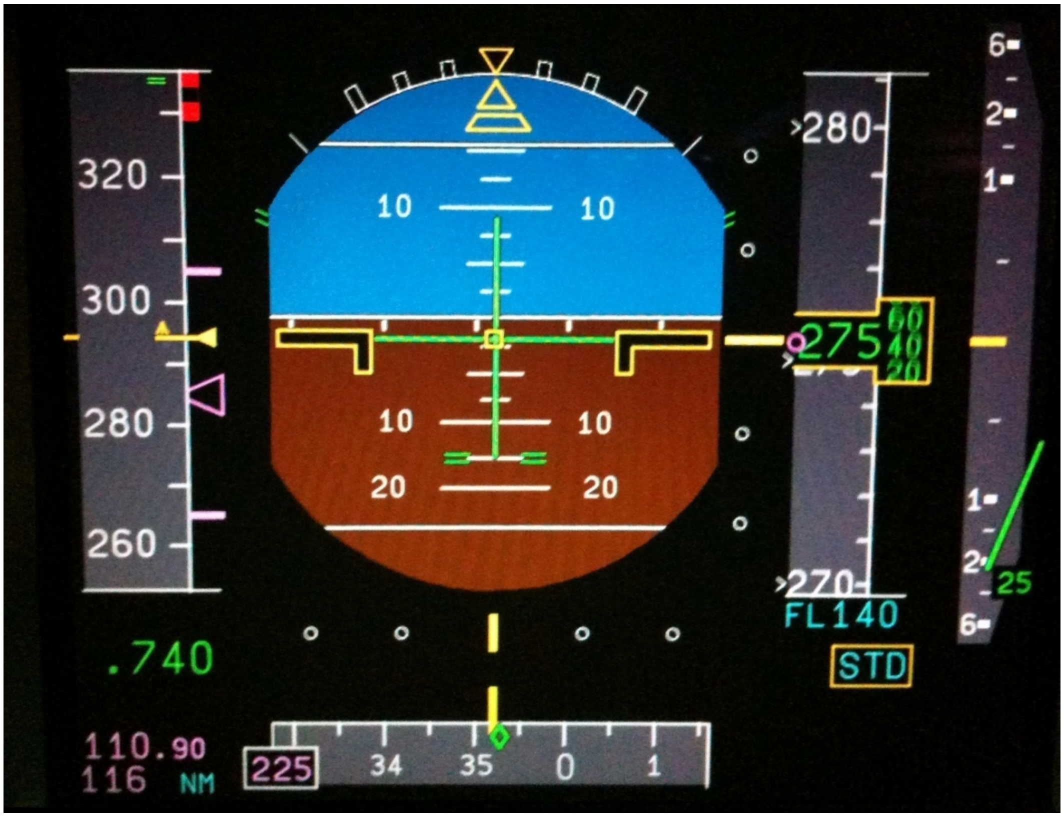


Figure 9: A320 PFD with Mach overspeed region displayed

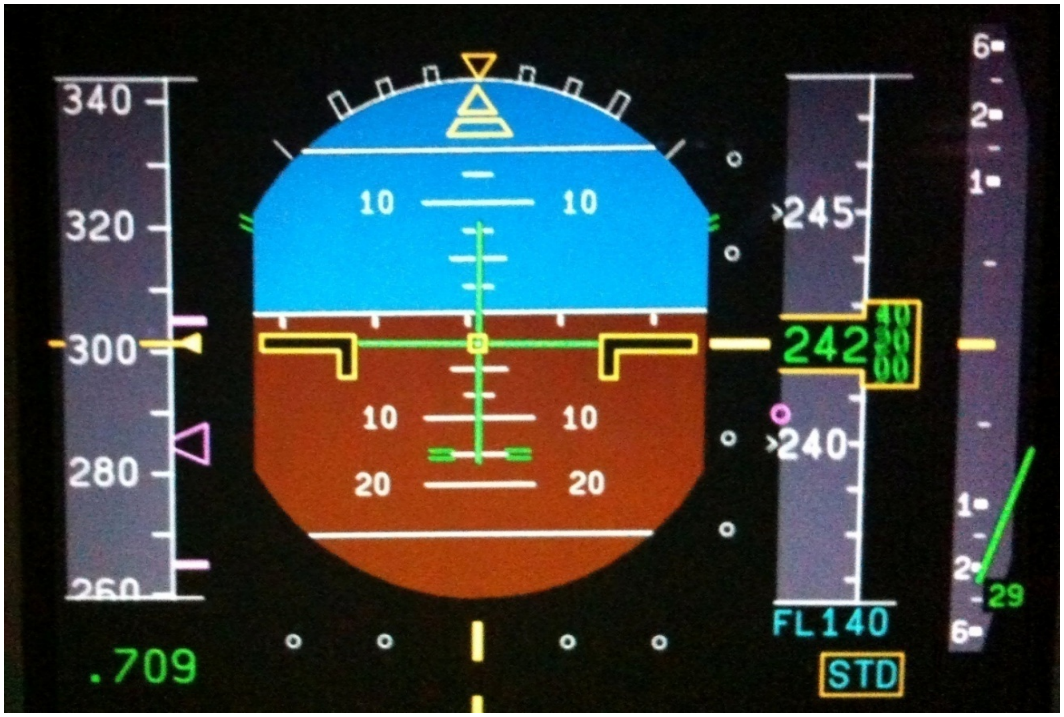


Figure 10: A320 PFD with overspeed limitation off scale

Not all the reference values disappear; the most important reference speeds are presented in an offscale manner (figure 9) when they exceed the normal range, but this is not an elegant solution. Understanding the difference between that speed and current system state now requires the operator to perform mental mathematics, rather than directly seeing the difference. Figure 11 shows the large number and variety of bugs and airspeed ranges that exist on the Airbus, presented in a practically impossible closeness and variety of aircraft flight modes for illustrative purposes. It seems clear we have come a long way from just presenting one system value on the tape display.

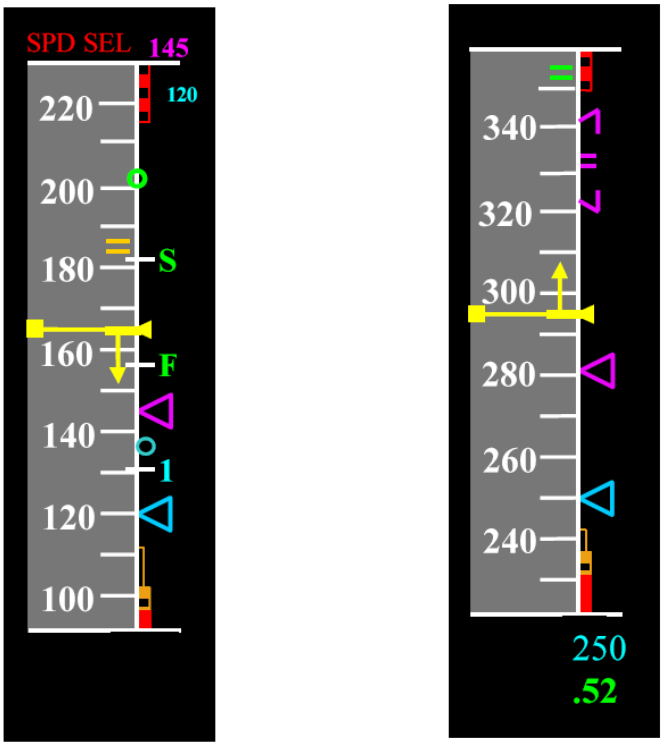


Figure 11: Airbus airspeed bugs and limitation ranges

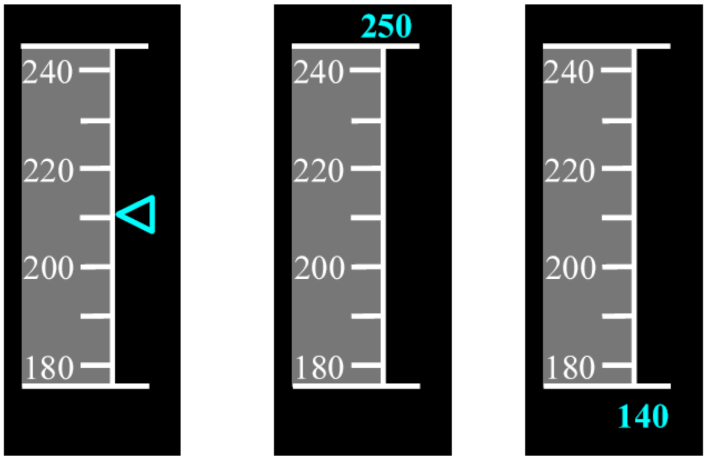


Figure 12: Airbus Off Scale Bug Presentation

The problem is that bug values can be close to system values, but not visible to the operator as they are moved off scale. The current partial solution is to present a numerical value offscale (figure 12) but this is limited to one or two values and requires cognitive rather than perceptual processing. The thesis proposal was that making the tape scale non-linear away from the center displayed value would retain the advantages of the current format while increasing situational awareness of system values that are presently off scale. (Using here mostly the first part of the definition of situation awareness “perception of elements in the environment within a volume of time and space” proposed by Endsley, 1995.) Modern electronic displays have the computational and graphical ability to produce such a display, something that was not possible with electro-mechanical tapes. But before presenting the experiment, let us review existing research into similar non-linear displays.

Chapter 2

FISHEYE MAPPING

Our normal human visual perception of the world is as an undistorted uniform linear Euclidean place; one in which as we move our eyes around, lines and shapes retain their solid relationships with each other. Differences in retinal size of similar looking objects are processed as evidence of an object's distance away from the eye. Using lenses we can create other depictions that have some advantages but also add distortions to our accustomed view. Extremely wide-angle lenses are known as fisheye lenses after Wood, 1906, found that refraction of light (governed by Snell's law) through a still water surface would produce for submerged fish a peculiar circular image of the world above. Fisheye lenses have an approximately 180 degree hemispherical field of view, and introduce a distinctive compressive distortion away from the center of the frame. Fisheye lenses were first put to practical use by meteorologists for panoramic whole-sky photographs (Hill, 1924). The first discussion of the use of fisheye views on a computer screen is generally cited as William Ferrand's 1973 Ph.D. dissertation (Ferrand, 1973). In 1976, Saul Steinberg drew a New Yorker magazine cover (figure 13) that caricatured a New Yorker's view of the world, perfectly illustrates a cognitive continuous focus+overview perspective. This much-imitated cartoon shows that fisheye views do not have to be precise geometric transformations, but can capture elements of the relationship of parts to a particular worldview. It also demonstrates that this approximate fisheye mapping can also be considered an exaggerated, but still ecologically recognizable, receding perspective view.

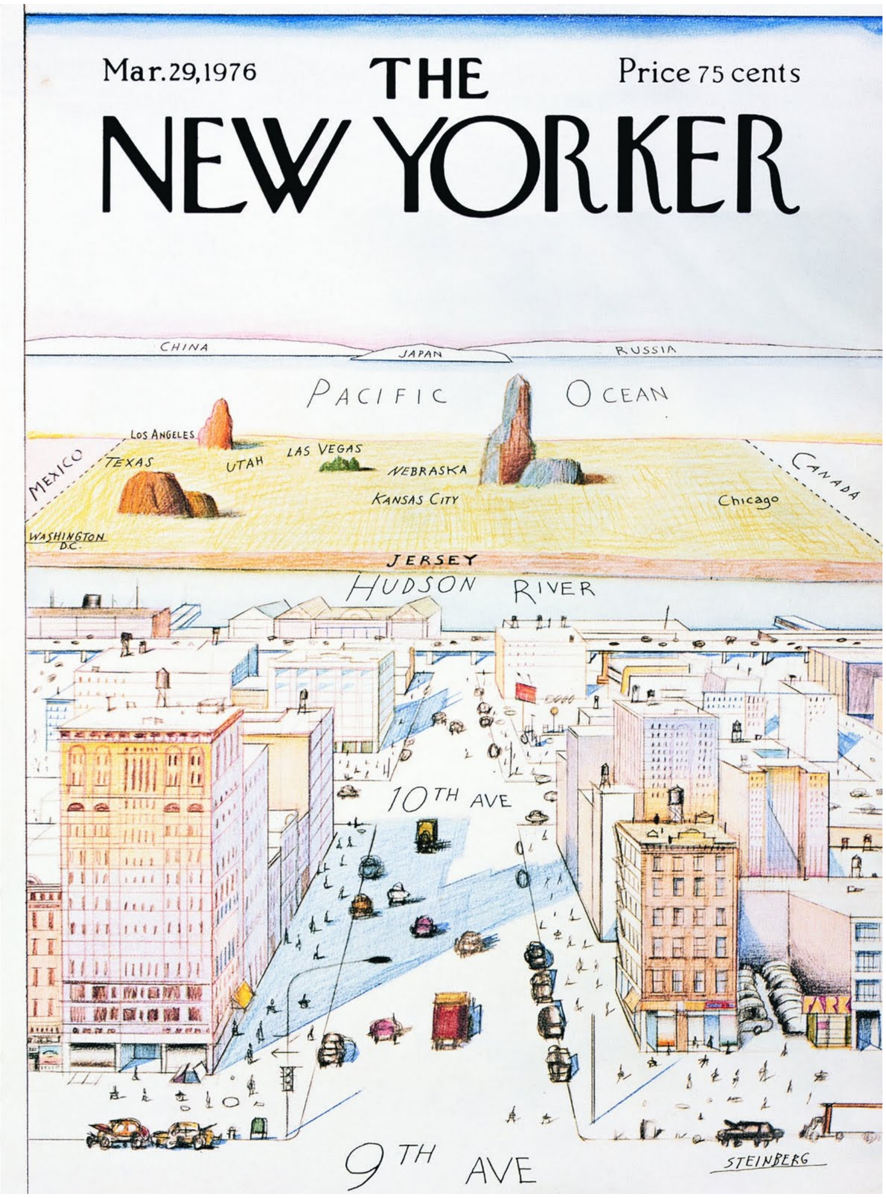


Figure 13: Saul Steinberg's 1976 Cartoon

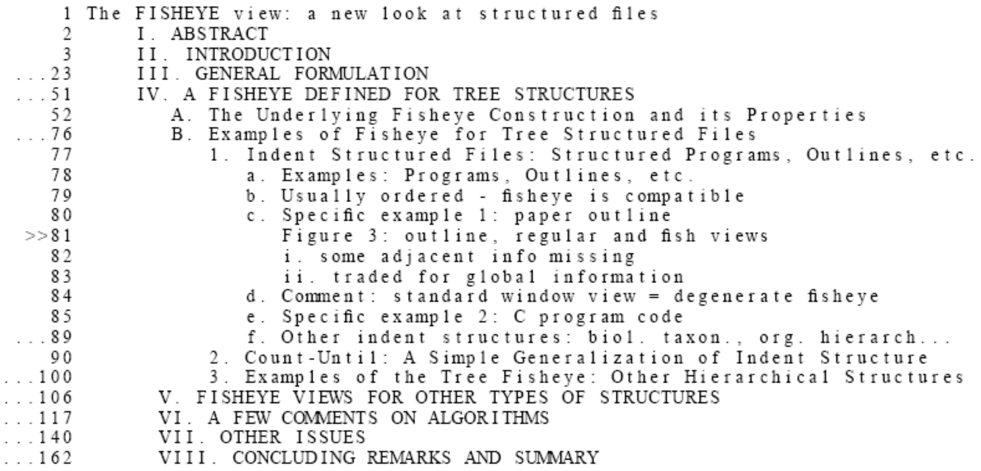
In 1981 George Furnas, then at Bell laboratories in New Jersey, published the idea of a fisheye distortion to present detailed information with its larger context. He considered the situation of conventional computer windows displaying long lists of files:

> The interface design problem amounts to deciding what parts of a large structure to show. . . . Current techniques generally involve a simple "flat window" view, showing consecutive lines of the file, with some mechanism for scrolling. In this arrangement, a small local piece of the structure is shown and the person has control over moving that locality over the structure. The problem with this method is that often the meaning or importance of local information derives from its position in a larger context. It is important to stay oriented, i.e., to understand where in the global picture this locality fits. The purely local views provided by standard flat windowing do not support this. (Furnas, 1981, p. 1)

He proposed using the metaphor of the fisheye lens:

> A very wide angle, or fisheye, lens used at close distance shows things near the center of view in high magnification and detail. At the same time, however, it shows the whole structure – with decreasing magnification, less detail -- as one gets further away from the center of view. There are several motivations for this approach. First, one typical reason people examine a structure is that they are interested in some particular detail. At the same time, they need context, i.e., some sense of global structure, and where within that structure their current focus resides. The idea is therefore to present detailed local regions, but to present selected important parts of the global structure as well. (Furnas, 1981, p. 1-2)

Furnas's idea of viewing files was demonstrated in the 1981 paper by a fisheye view of the paper itself, shown here as figure 14:



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     1 The FISHEYE view: a new look at structured files
     2     I. ABSTRACT
     3     II. INTRODUCTION
  ...23    III. GENERAL FORMULATION
  ...51    IV. A FISHEYE DEFINED FOR TREE STRUCTURES
    52        A. The Underlying Fisheye Construction and its Properties
  ...76       B. Examples of Fisheye for Tree Structured Files
    77           1. Indent Structured Files: Structured Programs, Outlines, etc.
    78              a. Examples: Programs, Outlines, etc.
    79              b. Usually ordered - fisheye is compatible
    80              c. Specific example 1: paper outline
  >>81                 Figure 3: outline, regular and fish views
    82                 i. some adjacent info missing
    83                 ii. traded for global information
    84              d. Comment: standard window view = degenerate fisheye
    85              e. Specific example 2: C program code
  ...89             f. Other indent structures: biol. taxon., org. hierarch...
    90           2. Count-Until: A Simple Generalization of Indent Structure
 ...100          3. Examples of the Tree Fisheye: Other Hierarchical Structures
 ...106      V. FISHEYE VIEWS FOR OTHER TYPES OF STRUCTURES
 ...117      VI. A FEW COMMENTS ON ALGORITHMS
 ...140      VII. OTHER ISSUES
 ...162      VIII. CONCLUDING REMARKS AND SUMMARY
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Figure 14: Fisheye file view, reproduced from Furnas, 1981

A similar Bifocal Display was described by Spence and Apperley (1982) in a paper that foretold much of the look and feel of Apple iPad and Microsoft Surface human/computer interfaces. A number of applications of fisheye views have since been created in several domains, and the practical possibilities are increasing in tandem with the processing speed and graphical clarity of modern computers. Examples include viewing a computer program (Furnas, 1986), the 3D visualization of a file system (Robertson, Mackinley, & Card, 1991), graphs (Sarkar & Brown, 1992), graphics-based aircraft maintenance data (Mitta & Gunning, 1993), surveillance (Lie & Toet, 1998), battlefield maps (Mountjoy, Ntuen, Converse, & Marshak, 2000), internet browsing (Yang, Chen, & Hong, 2003) and PDA calendars (Bederson, Clamage, Czerwinski, & Robertson, 2004). Fisheye views have been implemented for interactive environments where the system, as well as the viewpoint, is subject to change (Churcher, 1995). The first large-scale implementation of fisheye-type distortions was on the dock bar of

Apple's OS X (figure 15), which is visually appealing but has caused some problems with target acquisition (Cockburn, Karlson, & Bederson, 2008).

Figure 15: Mac OS X Dock Icon Panel

Figure 16 shows how a more modern graphical treatment of a fisheye text view looks in the relatively simple application of a user scrolling up and down a long menu list (compare to the constant font size of Figure 14). The Furnas fisheye is reported to have significant advantages over linear presentations in several applications (Hollands, Carey, Matthews, & McCann, 1989; Donskoy & Kaptelinin, 1997; Benderson, 2000). The fisheye distortion is one of many possible non-linear distortions that eliminate spatial and temporal separation by displaying the focus within the context in a single continuous view, for an excellent review of these focus+context constructs see Cockburn, Karlson and Bederson, 2008.

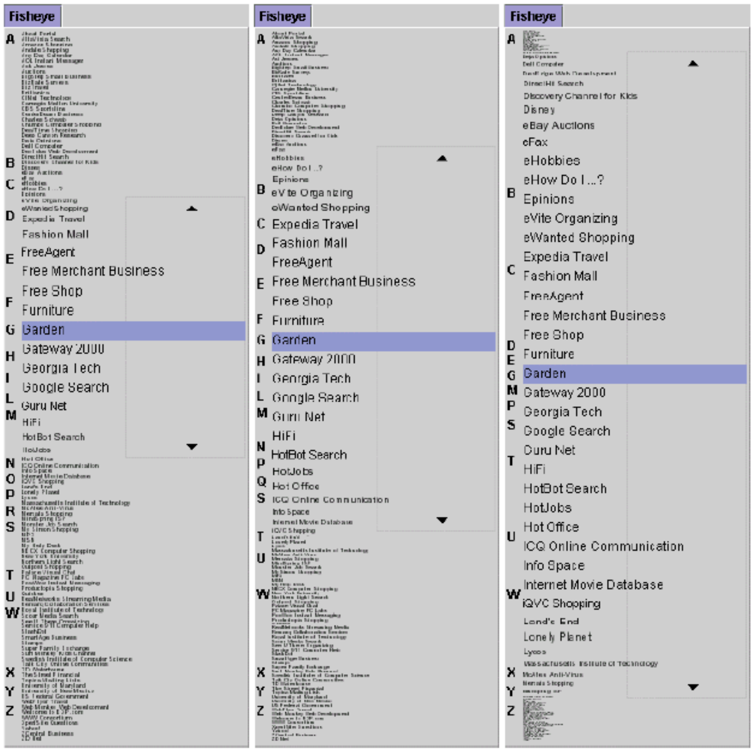

Figure 16: Fisheye menu views with multiple focus lengths, reproduced from Benderson, 2000

The tested tape display takes the form of this non-linear presentation, but inverts the relationship of the static and moving parts. The user does not move the focus up and down, but rather the tape moves up and down over a fixed central pointer. The reasoning is however the same; the fisheye presentation allows a detailed undistorted local view of the current system value while retaining relationship information to multiple, more global, system maxima and minima limits displayed with increasing compression as distance from the center increases. These other data can be dynamically represented on the tape display, and are viewable when they change values even without movement of the system value. Current tape displays only allow this for values visible within the limited range of the tape window, a limitation recognized by several authors. Hutchins writes:

> As technology changes, there is always a danger of discarding useful properties that were not recognized in the replaced technology. In their current form, the airspeed tapes that have replaced round-dial instruments in the state-of-the-art cockpits defeat some of the perceptual strategies of pilots. The new instruments offer few perceptually salient cues that pilots can map to their concept of fast/slow in the performance envelope of the airplane. This requires pilots to read the displayed speed as a number and to subject the representation of that speed to further symbolic processing in order to answer the questions that were answered simply by looking at the earlier display. (Hutchins, 2000, p. 69)

Harris, 2004, noted, “the windowed design can be quite poor at providing the pilots with anticipatory information. On the electromechanical counter-counter altimeter, the altitude ‘bugs’ were always visible.” (p. 87). Although new displays have been tested before entering service into aircraft, the aircraft cockpit may not yet be fully mature. Billings, 1997, reported that there were, “disquieting signs in recent accident investigation reports that in some respects our applications of aircraft automation technology may have gone too far too quickly, without a full understanding of their likely effects on human operators.” (p.34). Glass cockpits allow designers to present huge amounts of data, indeed:

> Information management technology has all but erased the problem of insufficient data in the system. Data, however, is not information. It becomes information only when it is appropriately transformed and

> presented in a way that is meaningful to a person who needs it in a given context. (Billings, 1997, p. 42)

Being able to present more bug and reference values graphically on the tape display would fit the principle of proximity compatibility (Wickens & Carswell, 1995; Wickens & Andre, 1990), a concept that is broken by (the common current solution) displaying important values numerically next to a graphic tape. Proximity compatibility is a movement towards expanding a single perceptual object display rather than forcing the human to cognitively integrate several inputs (Carswell & Wickens, 1987). The tested fisheye distortion is actually a more ecological presentation of airspeed and altitude data, modeling in some aspects both receding lines perspective and the fovea with its non-uniform distribution of photoreceptors over the retinal surface of the human eye. Furnas wrote:

> The fisheye [degree of interest] is implemented in human vision, though there is no distortion involved. Spatial resolution on the retina varies dramatically, by more than a factor of ten from the fovea to the periphery. By garnering detail only in the fovea, extracting a [fisheye] subset, the information that must be transmitted to the brain is dramatically reduced, and the sensory apparatus made much lighter and more mobile. (Furnas, 2006).

The display has a clear central detailed view with the focus on current system value, smoothly matched in the peripheral with other system limits in decreasing size and detail. Moreover, in the ‘real world’ things do get smaller and less detailed as they move further away from us.

Mitta and Gunning, 1993, concluded that the, “fisheye presentation strategy represents an analytical procedure for simplifying information. A simplification procedure of this nature may offer one means of reducing the detrimental impact of complex information on human performance.” Instrumentation has moved from being initially designed around mechanical practicalities (e.g. the pitot pressure driven round airspeed dial), to more human-centered electro-mechanical presentations (e.g. the tape airspeed indicator), to today’s fully electronic computer graphic presentations (e.g. the A320 PFD with its dynamic bugs and limitation arcs added to the tape display). We may now be overdue for a redesign of these displays to more match human perceptual and cognitive abilities. Writing in Science, Hirschfeld (1985) noted that, “more effort in display psychophysics will be needed to match instrument output to brain input. This includes such things as . . . nonlinear scaling” (p. 288).

Linear scales are preferred by regulatory bodies in civil aviation (“Linear scales shall be used in preference to nonlinear scales unless system requirements clearly dictate non-linearity to satisfy user information requirements.” (FAA, 2003, pp. 6-67)), in military aviation (Department of Defense, 1999) and nuclear power plant control rooms (Nuclear Regulatory Commission, 2002). However, there are already several approved nonlinear displays in common cockpit use. Figure 17 shows a pronounced non-linear airspeed indicator installed in a high performance sailplane. The degree of arc subtended between 80 KIAS and 60 KIAS is about the same as that for between 300 KIAS and 250 KIAS. Figure 18 shows a Boeing 757/767 airspeed indicator that expands the scale for the lower speeds used for take-off and landing operations while compressing the scale for higher cruise speeds. (It also shows the four white mechanical bugs set by the pilots and one computer driven overspeed limitation moving marker.)

Figure 17: Non-linear airspeed indicator, installed in a high performance sailplane

Figure 18: Boeing 757/767 airspeed indicator, reproduced from Hutchins, 2000

Figure 19 shows the Airbus instantaneous vertical speed indicator that sits to the right of the airspeed tape. It is also markedly nonlinear, being very sensitive for the first 1,000 feet per minute of vertical speed then becoming increasingly more condensed to 6,000 feet per minute at full-scale deflection. It is this kind of non-linear presentation that was tested for high range tapes.

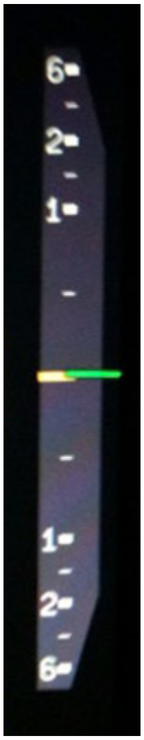

Figure 19: Airbus instantaneous vertical speed indicator

Although a nonlinear display may initially appear to be overly complex and possibly non-intuitive, it can also be considered as an ecological two-dimensional mapping of a three-dimensional round display viewed orthogonally from the axis of rotation — as for example in the wet compass used on boats and aircraft, figure 20. (These devices have the advantage of needing no external power to operate, but pose several human factors challenges to sailors and pilots who are actually viewing the (fixed in space) tail of the compass through a moving window and so have to turn away from the displayed numbers (FAA, 2008b)). Humans have become so used to turning combination locks, spinning dials, etc., that Apple's iPhone iOS operating system actually recreates this 'old-school' look in its user interface, shown in figure 21. The feeling of spinning wheels is quite compelling even though there is no actual distortion of the displayed values;

rather the shading is all that is required to create the illusion of depth (by atmospheric perspective, e.g. Bruce, Green, & Georgeson, 2003) and so imply the three-dimensional wheels. Figure 22 shows an EFIS approved for general aviation aircraft that has a non-linear mapping for the normally circular compass rose.

Figure 20: Wet compass, demonstrating non-linear mapping onto the retinal plane of a constantly spaced scale on a curved solid object

Repeat Never

Sound Bell Tower

Snooze ON

Label Alarm

Figure 21: Apple iPhone screen showing ‘dials’ display

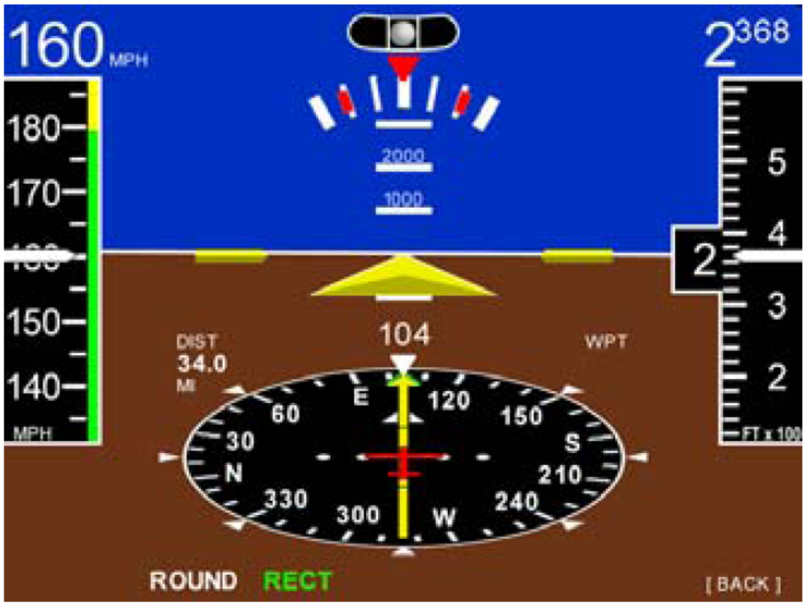

Figure 22: EFIS showing non-circular compass rose, reproduced from TruTrack Flight Systems, 2009

The acceptance of some non-linear displays in cockpits, the use of fisheye mapping in other domains and the precepts of ecological interface design all suggest that a non-linear tape display may be of value for systems with wide-ranges and dynamic reference values. Over thirty years ago, Stanley Roscoe wrote in Human Factors that, “during the 1950s and 60s, many promising flight display concepts were advanced that could not be implemented effectively with technology available at that time. With the advent of low cost, light-weight, and highly reliable microcomputing and display devices, good old ideas can be dusted off . . . and seriously considered for operational use.” (Roscoe, 1981, p. 341). The sentiment still rings true, but with today’s electronics we can now consider the ‘good old ideas’ from the 1980s.

Chapter 3

METHODOLOGY

The study consisted of presenting two versions of expanded range displays (and a unchanged control display) to naïve subjects. One of the tested displays was a relatively linear distortion from an idea first proposed as the Bifocal Display by Spence and Apperley, 1982, which was further developed as the Perspective Wall by Mackinlay, Robertson and Card, 1991 (figure 23). It provided focus+context with an undistorted center bracketed by two linear planes angled away from the viewer.

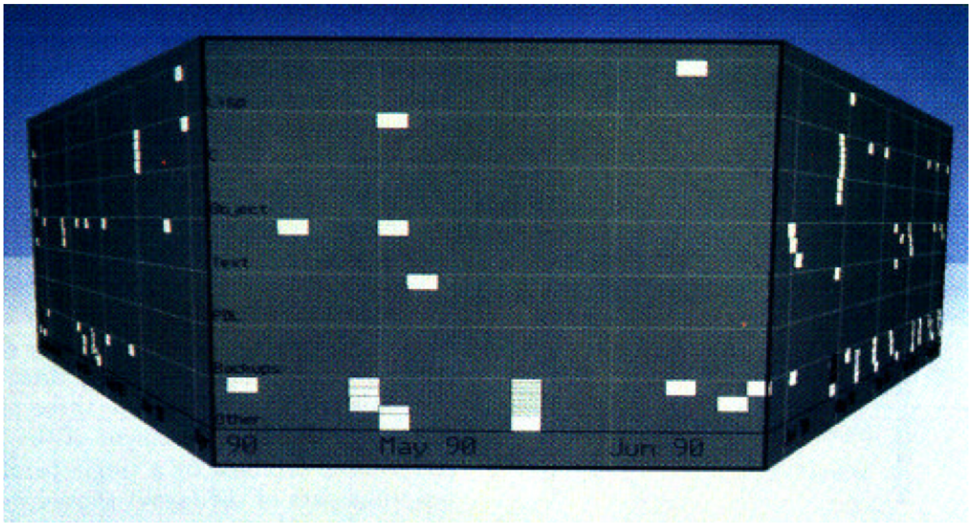

Figure 23: Perspective Wall, reproduced from Mackinlay, Robertson and Card, 1991

The second expanded range display was a completely smooth non-linear function fisheye presentation simulating the projection of a spherical counter. Both had compression in only one dimension, keeping the width of the tape even.

The amount of increased range was held essentially constant between the two expanded range displays.

MATERIALS AND INSTRUMENTS

Figure 24 shows two examples of control tapes, alongside the equivalent experimental two-tailed non-linear presentations that both increase the displayed range by approximately 60%. The fisheye presentation seeks to replicate the side view of a cylindrical counter. This gives an increase in range by a factor of π⁄2 (≈ 1.57). The perspective wall presentation is split into thirds, with an unchanged center and two tails each with a constant compression. A 100% compression would have given an increase in range by a factor of 5⁄3 (≈ 1.67), a little more than the fisheye view. To hold the range increase constant between the two modified displays and to maintain the same partition of the linear presentation into thirds, the tails were compressed by 85% to result in a total range increase of 1.57, the same as the fisheye.

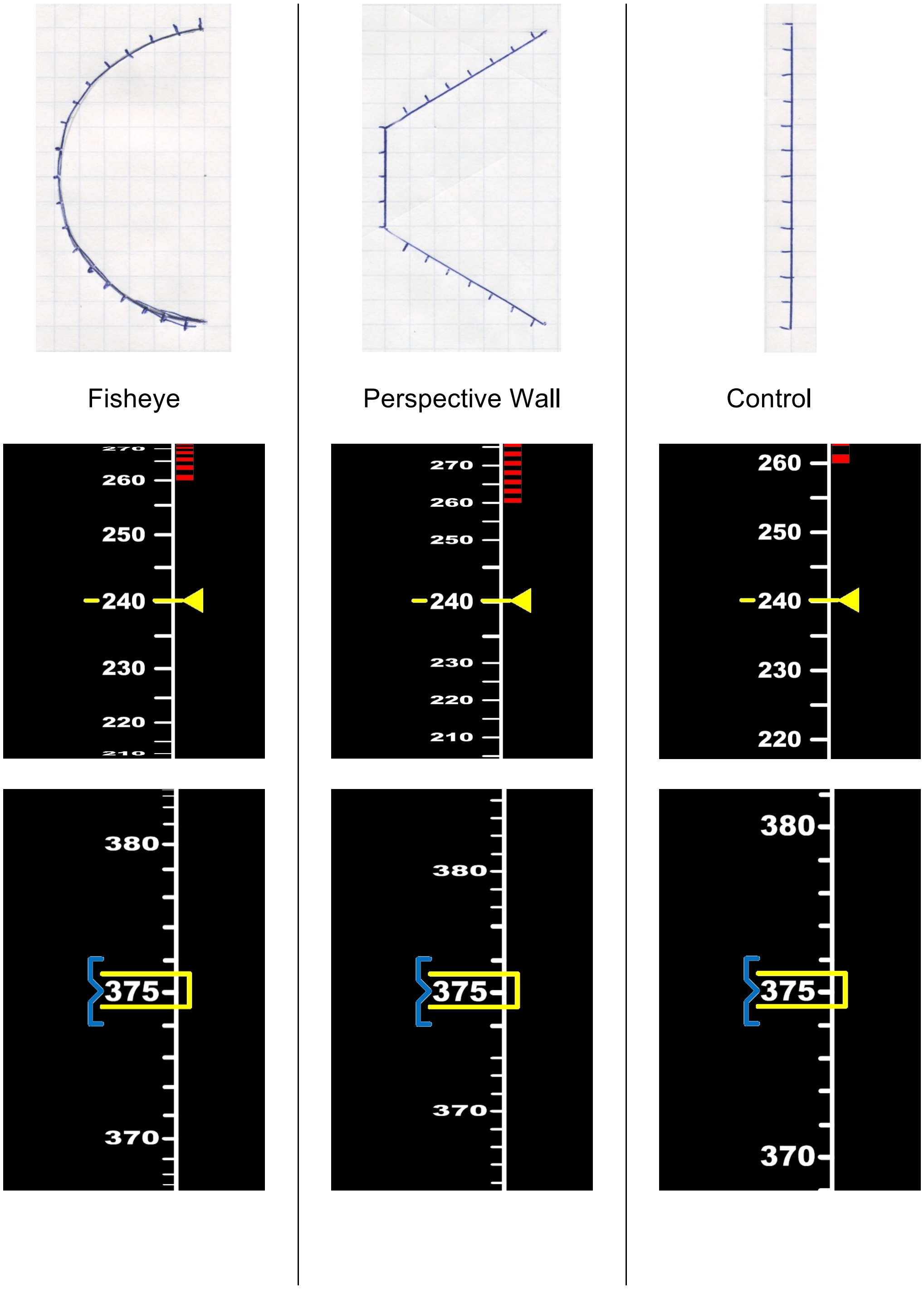

Figure 24: Examples of Control and Expanded Non-Linear Tape Displays Used in Experiment

Using current transport category glass cockpit displays as models, airspeed and altitude display were constructed using the computer program Paint.net running on a Dell XPS 410 PC with the Windows 7 operating system. Extended lengths of just the tape ladder elements were constructed in Paint.net with an increase in length of 1.57 times the replica control presentation. Then the images were manipulated using a custom written MATLAB program run on the same computer with MATLAB R2007a and the MATLAB Image Processing Toolbox version 5.4. The images were unchanged in the x-axis. The new tape ladder image combined with the unchanging cage elements of the display using Paint.net.

Inquisit 3 Web by Millisecond Software (Inquisit 3.0.6.0) was used to deliver the test images and record responses in both controlled laboratory conditions and remotely via internet delivery.

PROCEDURE

Mirroring the classic study by Grether (1949) both accuracy and interpretation time for the main system value were recorded, and in addition questions about the bugged values were asked and those accuracy and reaction times collected. After a short unrecorded practice session, each participant completed 36 trials (presented in a randomized order), with each trial consisting of viewing five ‘snapshots’ of a tape display, each lasting 500 milliseconds with a 2 second presentation of a distractor image (1970’s BBC TV test card, figure 25) at a central screen location in-between each tape image (to simulate normal instrument scanning practices). A typical sequence is shown in figure 26. This was followed by timed questions asking the main system value or the bug/limit values. Input was solicited by keyboard selection (1/2/3/4/5) of five possible values to allow for timing of responses without conflicting time requirements of moving a mouse or typing a three-digit value. The 36 trials each participant attempted were divided evenly between the two versions of the moving tape (airspeed/altitude), the three types of display (linear/fisheye/perspective wall), and direction of movement (up/down).

Figure 25: Distractor image shown for 2 seconds between tape presentations.

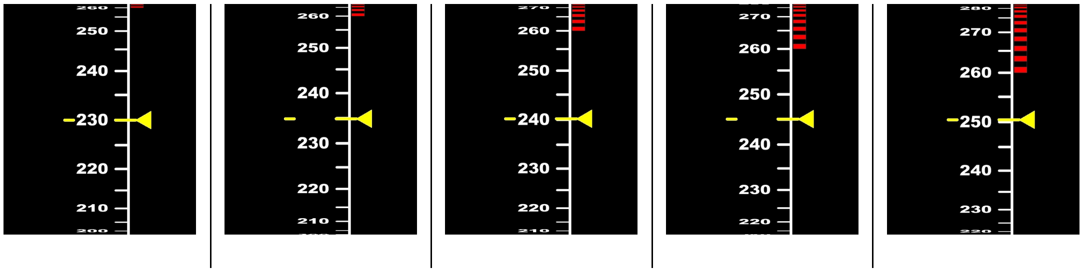

Figure 26: Example of Typical Progression (Fisheye/Airspeed/Increasing Values)

PARTICIPANTS

Twenty three (23) participants (7 male, 16 female) completed the experiment. All were ASU students who received course credit for participation. The only stipulations were normal color vision corrected to 20/20, and a minimum age of 18 years. Mean self-reported age was 22.8 (SD 4.5). The experiment was considered exempt after review by the ASU IRB, see Appendix A.

Chapter 4

DATA ANALYSIS AND RESULTS

The 23 participants yielded 828 trials. The reaction times are summarized in Table 1. A few of the times are exceptionally long, suggesting participants were momentarily attending to other tasks or disengaged from the trial goals. Defining exceptional as three standard deviations from the mean resulted in a reaction time of 9711 milliseconds, or almost 10 seconds. Eleven of the trials (1.3%) exceeded this time, and these data are removed from further analysis.

N	Range	Minimum	Maximum	Mean	Std. Deviation
828	37005	964	37969	3210	2167

Table1: Summary of Reaction Times (in ms.)

The overall correct answer percentages for the three types of display is 88.9% for the conventional tape, 89.3% for the circular fisheye and 89.5% for the linear wall. These differences are not significant *F(*2,814) = 0.03, *p* = .975.

Some of the questions related to the bugs/limits, and some questions related only to the main central display. The dataset can be divided to examine each type of question separately. The accuracy percentages for main display questions are 100% for the conventional tape, 96.7% for the circular fisheye and 100% for the linear wall. These differences are on the margin of significance *F*(2,272) = 3.05, *p* = .049. The accuracy percentages for the situational awareness questions are 83.3% for the conventional tape, 85.6% for the circular fisheye and 84.1% for the linear wall. These differences are not significant *F*(2,540) = 0.17, *p* = .843.

The overall times reaction times (in ms.) for the three types of display are 3060 (SD 1356) for the conventional tape, 3079 (SD 1277) for the circular fisheye and 2972 (SD 1246) for the linear wall. These times are not significantly different *F*(2,814) = 0.53, *p* = .590. As with the accuracy questions, the main system values and the bug/limit values can be examined separately. For just the main system question the reaction times (in ms.) are 3076 (SD 1145) for the conventional tape, 3098 (SD 1182) for the circular fisheye and 3088 (SD 1193) for the linear wall. Clearly any differences here are not significant. It is in fact quite remarkable how similar both the average reaction times and their distributions are to each other.

For just the bug/limit situational awareness questions the reaction times (in ms.) are 3052 (SD 1453) for the conventional tape, 3069 (SD 1326) for the circular fisheye and 2914 (SD 1271) for the linear wall. These results are less uniform than the overall reaction times. The bug/limit linear wall sample mean is more than 100 ms quicker than the conventional tape or fisheye, and the standard deviation of the conventional tape is higher than either expanded presentation. However, once again, these differences are not significant *F*(2,540) = 0.42, *p* = .660. A graphic representation of the data, figure 27, shows the slight differences overwhelmed by the overall variance.

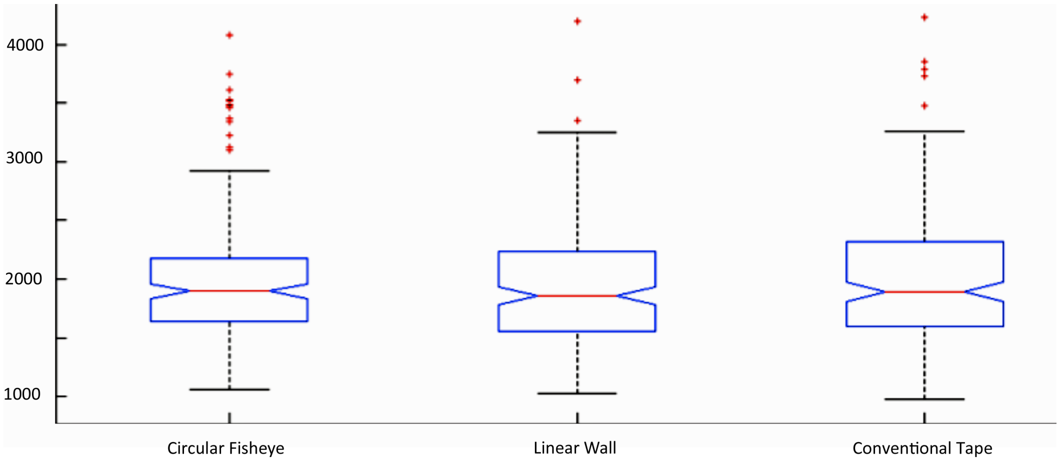

Figure 27: Box Plot of Bug/Limit Value Reaction Times

The reaction time analysis above includes values for trials in which the question was answered incorrectly. A cleaner analysis may be possible by removing reaction times associated with incorrect responses. However, the resulting overall response times (in ms) show no new pattern: conventional tape is 2959 (SD 1297), perspective wall 2934 (SD 1224) and circular fisheye 2959 (SD 1115). These differences are clearly not significant, $F(2,726) = 0.04$, $p = .965$. The experiment presented airspeed and altitude displays, the reaction times for correct response trials did not significantly vary between these presentations: airspeed mean 2869 (SD 1204), altitude mean 3034 (SD 1216), $F(1,727) = 3.38$, $p = .066$.

Chapter 5

DISCUSSION

It turns out that we have no nice neat graphs showing significant differences. No clear indication that in these tests the expanded range displays were better. But, we do have multiple indications that in 828 trials with 23 participants the expanded range displays did not adversely affect the speed or accuracy of retrieval of center system value. If there had been a reduction in the basic utility of the new display compared to the current construction then further consideration of the expanded range format would extremely hard to recommend.

It would be possible to construct a testing scenario that would (almost certainly) produce positive results for the expanded range displays. Consider the question posed in figure 28 and compare the conventional to the expanded range display. This would generate data with a huge effect size and statistical significance, but they would be no more informative than asking the truism “does a display with greater range show a greater breadth of information?”

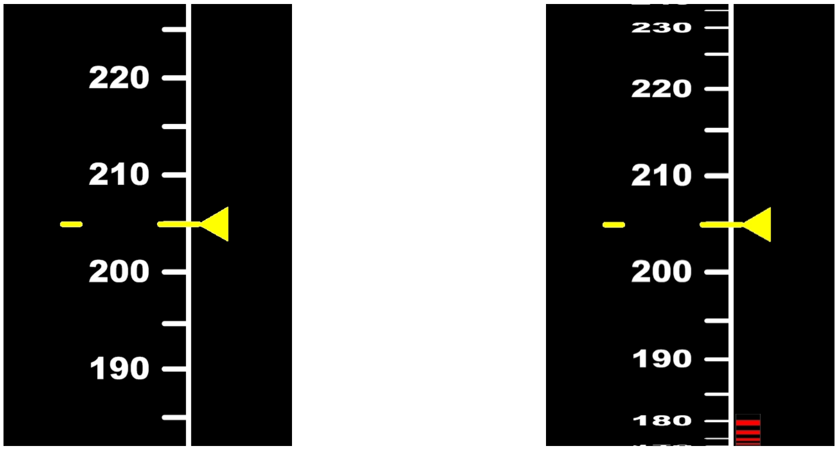

Figure 28: What is the value indicated by the start of the red warning area?

It would presumably be possible to create an experiment somewhere in-between the above example and the conducted trials. Such an experiment would produce nice looking charts showing statistically significant incremental increases in situational awareness. But it is highly questionable that such a construction would be a thing of value.

The real-world utility of this type of evolutionary expanded range display can only be truly explored by much more sophisticated simulation. The displays would have to be more temporally dynamic, and comprise but a part of a more complete system that tests speed and accuracy of primary system value and situational awareness as components of larger control and management tasks. However such simulations are very expensive. The value of the conducted experiment is in quickly determining if the new display makes simple interpretation of the primary system value poorer and/or slower; and so suggesting that any possible gains in situational awareness would be compromised by loss of basic function.

In this light, results showing no significant difference are positive. Empirical experimentation with multiple participants (rather than just an individual subjective beauty opinion) shows basic performance is not degraded, and suggests further simulation testing is warranted.

Limitations of the methodology include the use of a few static images to approximate moving tapes rather than actual moving dynamic displays, and the testing of the tapes individually rather than as a total cockpit package. Only the first part of Endsley's (1995) definition of situation awareness (perception of elements) is tested, a more complex experiment is required to have participants form mental models and show comprehension of meaning and projection of status into the near future. The experiment conducted is the first step (element development) in the three phases suggested by Weinstein and Ercoline (1993) for cockpit display evaluations (the other two being full-scale simulation and flight test). Since this testing was successful in showing the new displays do not compromise the basic center value function, it would be appropriate to move to simulation of moving tapes in a full instrument panel simulator to properly test the situational awareness changes for the bug/limit speeds.

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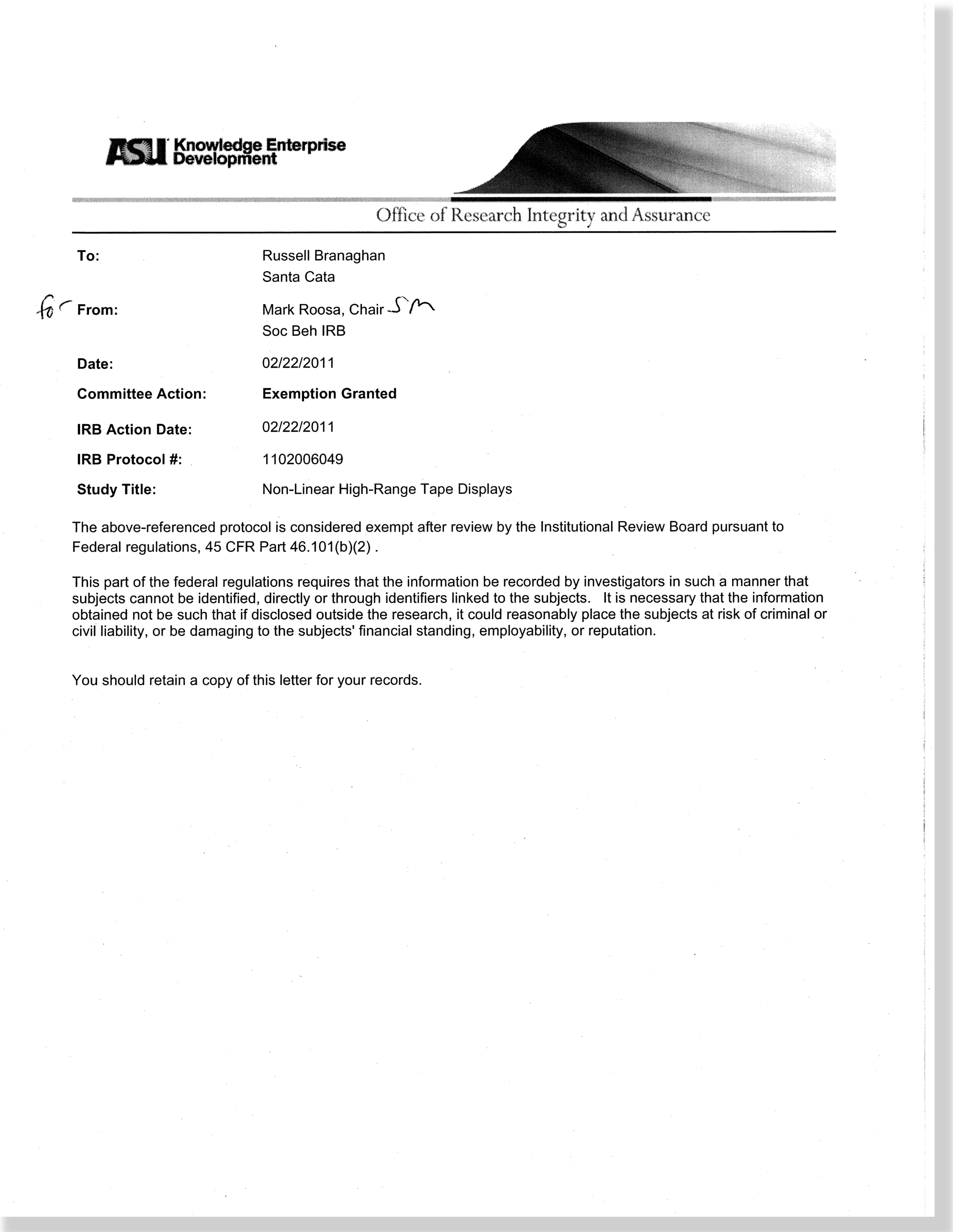
APPENDIX A

IRB APPROVAL



ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To: Russell Branaghan
Santa Cata

for **From:** Mark Roosa, Chair
Soc Beh IRB

Date: 02/22/2011

Committee Action: **Exemption Granted**

IRB Action Date: 02/22/2011

IRB Protocol #: 1102006049

Study Title: Non-Linear High-Range Tape Displays

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(2) .

This part of the federal regulations requires that the information be recorded by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that if disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.