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A MIND-REFERENCE FRAMEWORK FOR DESIGN AND EVALUATION OF INTUITIVE AND NATURAL INTERFACES

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The Mind-Reference framework is proposed to address new and existing interfaces at semantic, perceptual and contextual levels. This framework allows us to distinguish information structures at behavioral, physical and environmental levels. The framework deals not only with how the information is presented on a perceptual level but also, by accounting for a variety of task contexts, how a pilot can interpret that information. A design approach that follows this framework’s step-principles produces intuitive and natural interfaces for pilots and offers a benchmark for evaluation of existing interfaces.

The Problem

The need for intuitive and natural interfaces is a primary topic within the debate about the complexity of modern flight interfaces. Here we explore design principles that could be used to develop an intuitive and natural interface and how such an interface could be evaluated to determine that the presentation of essential information is intuitive to pilots?

Background

The framework detailed here was developed, in part, from a simulator study in which the pilots wore head-mounted video cameras throughout the flight. A modified version of a cued-recall debrief technique (Omodei, Wearing & McLennan, 1997) was applied to conduct pilot interviews using captured video footage. A structured interview during debrief uncovered the cognitive information strategies used by pilots. These methods revealed what is natural and intuitive to pilots as they use everyday information; how they collect, collate and understand information (Solodilova & Johnson, 2005). The framework incorporates principles that, if followed systematically within design and evaluation of a cockpit interface, will lead to an intuitive and natural presentation of information to pilots.

Birth of Framework

The framework consists of a Mind Reference information matrix that specifies structures, strategies, rules and step-principles to follow when designing or evaluating an interface (Figure 1). All dimensions of the framework, identified during the former study (Solodilova & Johnson 2005), are based on the analysis of how pilots work with information from their point-of-view throughout the flight.

The matrix is based on specific elements of information that pilots manipulate to make sense of their ‘information space’. These have been termed as Mind References, because pilots mentally collate and then store these pieces of information in the mind until they are needed. They are reliable and unchangeable pieces of information that are aligned relative to other, already established pieces of information (Figure 2).

The established pieces of information align into existing information structures that are constantly used in the aviation domain, for example the structure of flight stages. Structures are aligned Mind References that establish meaningful relationships in information among vast amounts of it.

Strategies are pilots’ approaches to and inventive ways of using the information layout to their advantage. Strategies help pilots deal with information effectively, for example to recover from a loss of or a rapid change of information.

Lastly, rules are essential guidelines that pilots learn by rote. These are taught to pilots in training and are reinforced through operational practice. Rules guide pilots to information that supports efficient and successful aircraft operation, for example “always be ahead of the aircraft’s action”.

An Information Matrix

The Mind Reference information matrix serves two purposes. Firstly, it shows the information levels at which pilots have problems, thus helping in the evaluation of interfaces to identify potential information problem areas. Secondly, during
Figure 1. Mind Reference Framework.

Figure 2. Information Space.
interface design and evaluation, it directs attention to possible solutions for issues related to information presentation and structure.

The matrix (Figure 1) has three dimensions of information: types of information understanding, types of information content and time dependent information. The dimension of understanding (i.e., how) is composed of three levels at which pilots have problems understanding information: perceptual, contextual and semantic. The information content dimension (i.e., what) consists of three areas of information that pilots need throughout the flight: physical, behavioral and environmental. The third dimension (i.e., when) consists of time dependent information about past, present and anticipated future. These are the three dimensions in which pilots manipulated information.

Use of the Matrix for Evaluation

Several current interfaces from the Hercules aircraft have been chosen as examples to show step-by-step how to assess whether information presentations are unnatural and non-intuitive for pilots. These examples reveal why some existing information presentation solutions are problematic.

Structures

As an example, a reference set/mode select panel (see Figure 3A) is evaluated using the framework. The panel is located on the glare shield in front of each pilot. Starting with the information matrix, it is necessary to first examine the information content using the content dimension (i.e. What) in relation to the set of buttons located on the right side of the panel.

Out of the nine buttons, four select basic behavioral parameters to maintain, such as IAS (Indicated Airspeed), HDG (Heading), VS (Vertical Speed) and ALT (Altitude). The remaining five buttons select more complex automation behavior. For example, the APPR button engages an automation mode to track the selected Instrument Landing System. The SEL button commands the automation to capture selected altitude in climb or descend. The NAV button arms selected navigation mode, and the A/T button engages autothrottle. CAPS is a nonfunctioning button. Thus, in our proposed design, we arranged these buttons into two sets of behavioral instructions, basic and more complex.

The next matrix dimension assesses levels of understanding of information (i.e., How), starting with the perceptual level. This dimension helps to determine the suitability of the button structure. The current structure has no recognizable information structure. Unnecessary introduction of any new structures can create an additional cognitive demand on pilots. The framework helps to identify an information structure that has the same or similar content already ingrained in pilots’ minds. The underlying assumption of this approach is that pilots will more easily associate with any new button structure if it conforms to an intuitive, already learned mental structure.

There is already an information structure that reveals aircraft behaviour to the pilot. It is presented on the six standard flight instruments on the panel of most aircraft. These standard instruments are the Airspeed, Turn Co-coordinator, Attitude, Heading and Vertical Speed Indicators, and Altimeter. The Hercules aircraft has these instruments arranged in a specific order on a Primary Flight Display and for our proposed design, we placed these in a single row: IAS, HDG, VS, ALT, as indicators of basic flight response.

Moreover, more complex automation behaviour is already announced at the top of the same display as automation modes, in the following order: A/T, NAV, SEL, APPR (see Figure 5). The only difference is that Autothrottle mode is announced inconsistently. On the Primary Flight Display it is announced as AT, but on the panel as A/T. This annunciation inconsistency needs to be corrected, unless there is a justification for the difference in annunciation.
According to evaluation through the behavioral and perceptual dimensions of the framework, the structure of lines on the reference set/mode select panel would benefit by reflecting the structure on the Primary Flight Display (see Figure 4). Line two should reflect the structure of basic behavior (i.e. IAS, HDG, VS, ALT), as present on the display. The top line should select complex automation behavior modes (i.e. A/T, NAV, APPR, SEL) (see Figure 5) with one additional swap between SEL and APPR buttons. This is dictated by the most basic structure of instruments on the display. Both lines should be ordered and positioned according to the existing structure on the display. For example, the Autothrottle button should be above the IAS button and the SEL button should be above ALT button, because bottom raw buttons (IAS and ALT) select corresponding complex automation behavioral modes (see Figure 3B).

![Figure 4. Primary Flight Display](image)

![Figure 5. Top of the Primary Flight Display.](image)

We have placed the CAPS button in the middle of the bottom row because that is the position of this symbol on the Primary Flight Display (see Figure 5 – vertical line on the middle of the display crossing the horizon line). However, the suitability of its position on the Primary Flight Display will be discussed in the next section, the semantic dimension of the matrix. Based on these two dimensions of the Matrix (What and How) out of three available, it can be established that the right hand side of a reference set/mode select panel does not follow established information structures and can be improved based on an existing structure of the same information that is familiar and in constant use by pilots.

Over a century of operation, aviation has established structures, to which pilots constantly refer. Among those are flight stage sequence, Air Traffic Control call order and other established configurations, such a T-instrument layout. These types of information structures are natural and familiar to all pilots and should be used in design, unless more cognitively efficient solutions can be discovered.

**Semantic level: consistency in application**

There are problems in the modern cockpit that are hard to identify with the evaluation methods currently used in industry (Singer, 2001; Newman, & Greeley 2001). Pilots have difficulty understanding and interpreting available information (Sarter & Woods 1994; 1995). The semantic level of our matrix offers a solution. Although most of the information on the Primary Flight Display has a perceptually plausible interpretation, some features in close proximity to each other offer contradicting meanings.

Consider the following: A ‘Fly towards’ or ‘Fly-to’ principle has been introduced to the modern cockpit. Most features on the Primary Flight Display, such as Flight Director cues or TCAS RA (Traffic Collision Avoidance System) comply with this principle. However, when features are presented side by side and do not follow the same principle (i.e. How – semantic level), confusion can result at a critical moment of operation. The semantic level of the Matrix offers evaluation of such presentation and helps to bring interpretation of the display into one ‘semantic principle’.

Several features on the Primary Flight Display comply with ‘Fly-to’ principle, e.g., Glideslope Indicator, CAPS speed bug and Integrated Flight Director. The Integrated Flight Director, for example, gives the pilot precise trajectories for ease of flight control. However, other features on the same display do not follow the same principle and in fact demand the opposite response (i.e. ‘fly away’) from the pilot. This can create confusion and an incorrect response on the part of the pilot. The features that do not
follow the ‘Fly-to’ principle are the Speed Error Tape, the Acceleration Cue and the CAPS Distance tape. If the Speed Error Tape is below the Climb/Dive marker it means the aircraft has deviated from and is below the required speed. The pilots’ response should be to increase speed. However, if the pilot interprets this as a ‘Fly To’ principle, which is possible since the feature is attached to another feature that complies with this principle, the pilot could potentially respond incorrectly and put the aircraft in an undesired position.

There are also less obvious problems that are semantic in nature. These would not appear to be problems if the pilot were to memorize the meaning behind each feature or word. However, if the pilot forgets the feature’s meaning and needs to search for a possible logic behind each feature to establish what it means, errors are likely. Consider the following example.

A Non-Directional Beacon is represented as a triangle. Although the Non-Directional Beacon does not provide direction, the triangular shape of its symbol could be interpreted as a directional arrow. In contrast, a Directional Beacon is represented as a circle, which does not suggest direction via its visual properties. A better solution would be to exchange these symbols. The Non Directional Beacon could be represented as a circle to indicate the ‘point of origin’ for a signal and the Directional Beacon could be represented as a triangle so that the directional cue was embedded as a visual property.

The semantic level of the matrix directs the evaluation team to identify whether the symbology and presentation of information is optimal, familiar to pilots and has no double meaning behind it.

There is a similar semantic problem related to interpretation of signs on the Head Up Display. However, here the third contextual level of the matrix’s understanding dimension directs attention to interpretation of symbology that can be influenced by the context in which it is presented.

The Pitch recovery feature, termed the ‘Chevron pairs’ (^^) indicates that the nose of the aircraft is high. In doing so, it clashes with the ‘Fly-to’ principle that is also applied on this display. Furthermore, the pilot can interpret this feature as a command to ‘recover up’, because it appears as two arrows pointing upwards. In following this signal, the pilot would put the aircraft in an unusual attitude.

The more problematic issue with ‘Chevron pairs’ is that there is a similar feature that indicates a nose-low attitude, but is represented as a single Chevron (^) and actually this time does show the recovery direction (i.e. ‘Fly-to’ principle). If the pilot misinterprets one of these chevrons (Figure 6), the aircraft would be recovered in the wrong direction which again would result in the unusual attitude. The semantic level of the matrix emphasizes the importance of avoiding symbols that have double meanings or that, due to context, can be interpreted in different or contradictory ways.

### Figure 6. Chevrons

**The use of Framework step-principles**


During evaluation, the interface should be judged against each step-principle. Here, we provide an example of how a designer would apply the step-principles for interface evaluation.

**Environment level: information proximity**

The framework’s principles 6, 7 and 8 emphasize the importance of linking and grouping complementary information as well as representing meaningful relationships between related information. The location of interdependent information that is spatially separated and without other forms of association should be identified during evaluation, especially if this information is naturally and routinely used in conjunction with each other.

The readings of barometric pressure and altitude are interdependent pieces of information. On the Head-Up Display, barometric pressure is separated from altitude even though the accuracy of the altitude reading depends on barometric pressure. The seriousness of this problem has noted in a survey of forty-six pilots, where nearly half of the pilots reported that they had set the wrong barometric pressure or had seen another pilot do so (Demagalski, et al 2002).

The DME (Distance Measuring Equipment) information is similarly away from the other related
navigational data, such as the source of navigation information. If the pilot reads the navigation information correctly, but it is from the wrong source, that information is of no use.

Both of the problems described above were identified via the framework’s evaluation step-principles.

*Step-principle 9: ‘relative to’*

Step-principle nine of the framework proposes that all measurement related information has to be represented in comparison to and relative to either the limit or capacity of the parameter it represents. The automation has operational boundaries that are programmed into the system, some of which pilots need to know. During climb, for example, the selected NAV (Navigation) or ALT (Altitude) automation mode may not capture course or altitude respectively if there is a large deviation. The automation tolerates the deviation only within specific limits. The altitude will only be captured within 10\% of the rate of climb and the course will be captured only within 5\% of the selected course but not otherwise. These limits are not announced to the pilot who can remain unaware of why the automation did not accomplish the commanded operation (i.e., capture NAV or ALT modes).

The above example illustrates the application of step-principle nine and the importance of presenting limits and operational tolerances for automation. Those limits should be identified during design. If not identified during design, they should be detected during the evaluation.

**Conclusion**

The framework outlined here was developed initially from systematic observation and analysis of operational video data of pilots during simulated flights. The analysis emphasized the use of information from the pilot point-of-view. This emerging framework offers guidance for both design and evaluation of information structures behind modern cockpit displays.

Continuing advances in flight displays and automation have imposed new ways to fly and new ways to interpret information on pilots, but further innovation of the information structures behind the displays is not always desirable. Instead, there is considerable advantage in returning to the basic concepts of flight and the basic strategies of piloting to understand the mental processes that have become ingrained within the aviation profession. New technology and automation offer radically new ways of representing information and of controlling an aircraft but the design of these technologically advanced systems must be constrained by mental structures that pilots find natural.

The modern cockpit of the Hercules is not the only one that can benefit from use of the Mind Reference framework for design and evaluation. Modern commercial aircrafts, such as Airbus 320 and Boeing 777, have been evaluated using this framework and similar problem areas were found in cockpit interfaces, where improvements can be made to make interfaces more natural and intuitive to pilots.

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