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Principles for Human-Centered Interaction Design, Part 1: Performative Systems

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Previous installments of this department have discussed human-centered principles for the design of intelligent systems.[1–3] In this installment, we present human-centered computing (HCC) principles specifically for the design of interaction in performance contexts. We refer to this as *interaction design* because the goal for design is to support macrocognitive work. Thus, we find the traditional terms "display design" and "interface design" to be misleading. Visual interfaces are one component, albeit a crucial one, to intelligent systems that have to convey the state of the world and the actions that the operator might take in an interdependence relation with the technology.

Additionally, we refer to *performative systems* rather than "performance support systems" because this traditional term also carries misleading historical baggage. Many, if not most, so-called performance support systems are actually control systems: they control operators by dictating their action sequence. In a performative system, the operator uses the technology to understand certain aspects of the world and determine the actions to take, as in industrial process control or flying an airplane. In a forthcoming installment of this department, we will discuss principles for what we call *observative systems*, in which the operator uses the technology to understand certain aspects of the world, and then use that understanding to develop further insights for use either with that technology or outside of it. A clear example would be weather forecasting: The technology that forecasters use does not influence or control the weather. We admit to drawing a fuzzy line. While forecasters do not use technology to influence what they are observing (the weather), the technology is used to understand the weather so that other things can be influenced (for example, by their public and aviation forecasts). We should therefore perhaps refer to systems that are *primarily* performative or *primarly* observative. Despite the need for such hedging, we feel that the observative versus performative distinction has some use.

The HCC perspective takes the term "human centered" to mean more than simply "considering the user" in the development of technology. Beyond that, HCC means placing our understanding of people and their activities at the forefront of work system design. A human-centered system must amplify and extend the human's perceptual, cognitive, and performance capabilities while at the same time reducing, and in some cases eliminating, mental workload.

A Human-Centered Cockpit Display

Using conventional cockpit displays, pilots must scan individual dials and instruments to get the information needed to maintain their understanding of the state of the aircraft and ensure that it is performing as intended. Displays such as that shown in Figure 1 use instruments that display the values of individual variables in a variety of units: degrees, knots, feet, rates of change, and so on. Pilots must integrate these pieces of information into their mental model of flight to understand flight performance.

OZ is a novel cockpit display initially conceived by going back to basic principles in vision science and aerodynamics.[4,5] The goal was to eliminate the need for an instrument scan. But how could this be accomplished?

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Figure 1. An emulation of a traditional dials-based cockpit display.

Focal versus Ambient Visual Fields

The focal channel in human vision is used for directed attention tasks such as reading; the ambient channel is primarily for tasks (such as locomotion) that can be accomplished without conscious effort or even awareness. In normal circumstances, both channels are simultaneously active.[6] Reading conventional cockpit instruments requires using the focal channel sequentially, glancing from dial to dial, while the part of the visual system optimized for processing locomotion information—the ambient channel—isn't entrained by instrument-based cockpit displays. OZ exploits the focal channel but also the ambient channel's wide field-of-view to enable the apperception of multiple information streams simultaneously. Figure 2 shows screenshots of the OZ display.

Visual Primitives

To harness both focal and ambient channels, the graphic elements in the OZ display use simple visual perceptual primitives—dots and lines. These are resilient to optical and neurological demodulation and can pass information through both the ambient and focal channels.[7] OZ organizes these visual primitives into meaningful objects using well-known principles from visual perception, including figure-ground, pop-out, chunking, texture, effortless discrimination, and structure-from-motion.[8,9] These principles explain the direct perception of horizontal and vertical displacements of the "starfield" background. The "stars" are layered and move toward the observer as the aircraft moves, creating apparent altitude layers and heading columns. The columns in the starfield represent compass headings. The long blue horizon line indicates the aircraft's altitude and orientation, and can be maintained coincident with a row of stars to ensure that the aircraft is holding at a particular altitude.

OZ also presents a stylized "aircraft" metaphor composed of lines and circles whose location within the starfield metaphor shows attitude and flight path information. In the fixed-wing version of OZ depicted in Figure 2a, the central circle is the nose ring depicting the aircraft's flight path. The short horizontal line indicates the aircraft's up or down pitch. The vertical line emanating from the top of the nose ring is the stick, which indicates bank angle. The line emanating from below is the pendulum, which depicts the slip or skid resulting from an uncoordinated turn.

To the left and right of the nose ring are a vertically symmetric pair of bent wings, a multicolored straight wing, and a dual-colored vertical connection between the wings, called the power bar. The straight wing is a speed scale, with the power bar's placement along the straight wing changing to indicate the aircraft's speed. The end of the straight wing closest to the nose ring depicts the stall speed without flaps, and the outermost point is the "never exceed" speed. The wings and wing elements depict other flight aspects as well—for example, the bent wings are the stylized representation of the aircraft's lift-to-drag curve. The inflection point in the wing is the speed at which the ratio of lift to drag is maximized and holds special significance for many flight operations.

In general, the shape, movements, and interrelationships of the graphical elements in the aircraft metaphor represent the aircraft's configuration, airspeed, engine output, and flight envelope. The wings and power bars depict the interrelationship of power, drag, airspeed, configuration, and performance. As a consequence of this design approach, OZ produces an immediately perceivable depiction of aircraft state and performance, which the pilot would otherwise have to construct and maintain as a mental model.

Frames of Reference

Merging the aircraft and starfield metaphors, OZ presents a common frame of reference to bring together

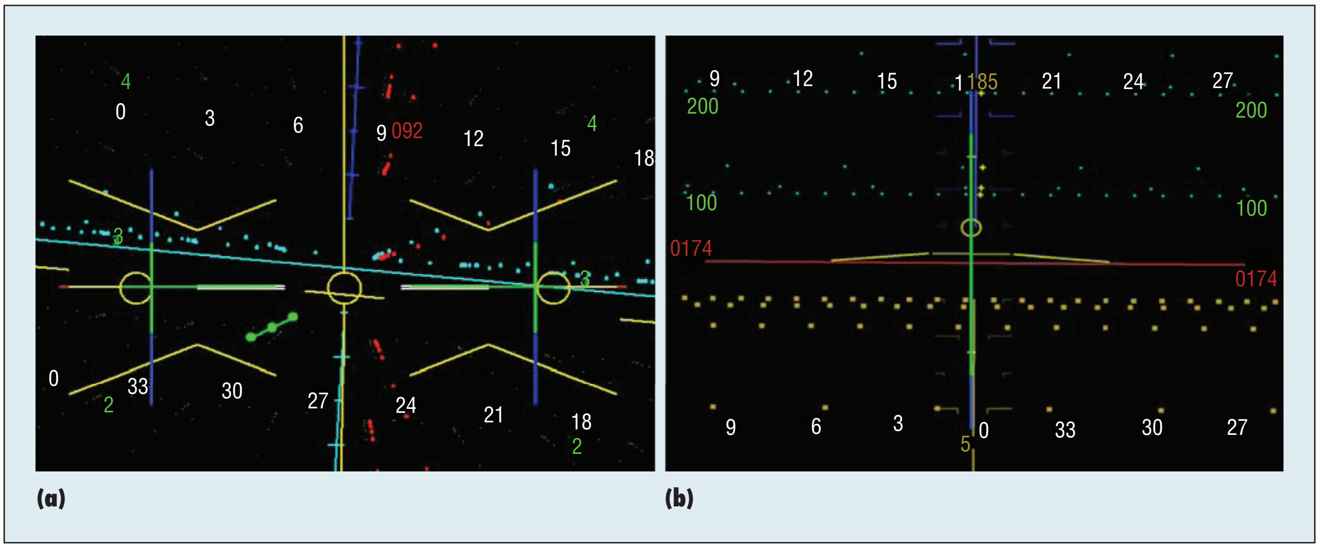

Figure 2. Screenshots of OZ displays for (a) fixed wing and (b) rotary wing aircraft.

all cockpit information in a single display. An integrated frame of reference provides the structure that transforms separate perceptual objects into an ensemble of meaningfully interactive components. This is one reason that OZ can communicate spatial orientation, aircraft location, flight performance, aircraft configuration, and engine status all in the time it takes to look at a single conventional instrument—as proven by experiments. Note that all of the alpha-numeric information presented in a conventional display (such as in Figure 1) is also presented in the OZ display—it's just presented in a way that stresses the meaning of the numbers rather than the numbers themselves.

So why is this display called OZ? During one of the experiments, a technician had to work behind the cockpit simulator. The participant was told to disregard the technician's activity. In the case of the OZ display, the "man behind the curtain" is the computational analysis that integrates the flight data to drive the display elements.

When experienced pilots first see OZ, they're sometimes taken aback, often regarding the display as more like a video game than a serious cockpit display. However, the learning curve is very short. Using a flight simulator, experiments have demonstrated superior flight performance for both experienced pilots and practiced non-pilots. Pilots can quickly learn to fly using OZ, and indeed can fly better in OZ under turbulent weather conditions. They can fly more than one plane simultaneously (which has clear implications for the operation of unmanned aerial vehicles). They can even fly successfully when a significant portion of the total OZ display is masked, a reflection of the power of presenting flight information in a way that capitalizes on the ambient visual channel. A helicopter version of OZ (Figure 2b) results in significant gain in the effectiveness of training in the difficult task of flying and hovering that specific machine.[4]

Because the OZ display elements are constantly in motion, Figure 2 doesn't do it justice. We invite you to visit http://oz.ihmc.us and download the displays.

Display Design Principles

OZ relies on several design principles. These principles resonate with approaches such as work-oriented design in the field of human factors, and ecological interface design in the field of applied psychology.[10,11] Indeed, OZ is a perfect example for those approaches.

Principle 1: Exploit Psychobiology

We introduced this principle earlier by invoking the notions of visual fields and perceptual primitives. In one experiment, we demonstrated the power of combining visual fields by having the pilot maintain straight and level flight in various degrees of turbulence while simultaneously reading aloud from text displayed in the central portion of the OZ display. Even novice pilots could do this task, performing just as well as when flying without the reading task. With the conventional display, performance was degraded significantly by turbulence, even when the participants didn't have the secondary reading task. Adding the secondary task of reading was simply impossible for the participants with a conventional display.

These results might be at least partially explained by the independence of the information-carrying capacities of the ambient and focal visual channels. By utilizing ambient and focal visual channels together, OZ communicates to the operator more data in the same amount of space as the conventional instrument array, but does so simultaneously.

Principle 2: Present a Normative Model of the Task

It's critical that the display reflects a faithful model of the tasks as they're understood and performed by the operator. If there's flexibility in how the task can be performed, the interface will be required to support it. The desired result of this principle is that the operator can simply look at the screen to determine system status, required actions, and amount of correction, rather than having to interpret low-level data by updating a mental model.

Operationalizing this principle begins with determining the requirements for the task. This is easier in certain domains. For example, in the aviation domain, more than 100 years of aviation psychology has told us what information is necessary to fly an aircraft. Therefore, an OZ display for aircraft could take in the same data as is shown by traditional instruments. In cases such as this, the domain is already bounded and the search for a performance-improving interface can be primarily a matter of visual design, rather than determining basic data needs in addition to visual design.

OZ presents a graphic depiction of aircraft performance that the operator would otherwise have to construct and maintain as a mental model. This enhances flight performance for several reasons. First, it reduces the operator's requirements to recall the currently correct model. Second, it reduces the amount of mental calculation required to apply the model to current conditions and determine the amount of correction. Third, it can ensure that all operators use the same model, so handoffs go smoothly. The overall result is that OZ shifts the workload requirements for flight from one of visual scanning requiring intensive integration to nearly instantaneous or "direct" perception of an integrated picture.

As illustrated especially in the OZ fixed-wing display, the depiction of a normative model of the task need not be a physically realistic or "natural" representation, or even an intuitively obvious one. This is contrary to the dictum of naturalness of representation.[12] Although it might take some training to understand the semantics of the metaphors used in the normative model, if the symbology is used consistently and is unambiguous, the time to learn shouldn't be too long. This typically involves constructing metaphors for the system being controlled as the foreground of the display and using the background to show the context in which the system is operating. For the OZ display, the foreground is the aircraft metaphor; the background is the starfield metaphor. Developing the normative model of operation in this way enables the use of the background metaphor as a scale that the foreground metaphor can be matched against.

In domains where the requirements are already known, we can also readily determine what makes learning and mastering a task difficult when the existing or legacy interface is employed. These are exactly the things that we wish the new interface to address: making the task easier to learn as well as making it easier to master the difficult skills required in the domain (see Principle 8). In cases where the requirements aren't known in advance, the interface designer's task is much more difficult: alternatives in the requirements space must be explored as well as alternatives in the visual design space.[10,11]

Principle 3: Provide an Integrated Frame of Reference

In current flight displays, streams of data are only related to each other in the pilot's head. Moreover, the flight instruments aren't integrated with other instrumentation such as engine instruments. The traditional solutions to this situation have been to severely limit flight procedures, to emphasize instrument scan training, and to require extensive pilot experience.[13]

The frame of reference for OZ is a coordinate system that maps to latitude, longitude, and altitude, and relates those as angular displacements. The rows of the starfield are projected on to this coordinate system to show altitude layers, and the columns of the starfield indicate headings. The projection allows OZ to display 180 degrees of heading across the top of the screen, with the reciprocal 180 degrees indicated along the bottom. The center of the screen is the zero point of the projection, representing collocation with the aircraft. This zero point is shared by other structures in the OZ display, providing a consistency of motion and reference. For example, the center of the screen also represents the zero point for airspeed, heading, and aircraft horizontal and longitudinal axis. This enables easy understanding of all of these aspects of the flight task.

Principle 4: Show What the Data Mean

Although the requirements for a domain might specify that the operator needs to know particular data values updated at some rate, this often doesn't go far enough. The data streams come from different sources, differing in importance and using different scales and frames of reference. Usually, the streams don't cross—that is, they don't have any explicit relationship with other streams—except in the operator's head.

OZ obviates the mental operations that would integrate the raw data before the data can be used to make a decision. By doing so, the operator can make decisions based on a flow of processed data, presented in a way that makes common, important, or critical tasks matters of immediate apprehension. Thereby different types of information are processed simultaneously, rather than serially. This principle is foundational for OZ, and critical to reducing unnecessary cognitive load.

An example of this principle is the OZ depiction of stall speed. With conventional instruments, determining that an aircraft is approaching stall speed requires first remembering the numeric value of the aircraft's stall speed, then looking at the speedometer, matching the needle to the underlying scale, and interpreting the number pointed to by the dial. Then the number needs to be integrated into the pilot's mental model of the context and state of the aircraft (such as weight, landing gear position, and G-force) to determine the significance of that number. In the OZ display, as the power bars approach the inboard ends of the wings, the operator knows that the aircraft is approaching its stall speed. He or she doesn't need to remember the actual stall speed of the aircraft for the given configuration, weight, or g-loading.

Principle 5: Separate the Degrees of Freedom

One of the key difficulties in learning to hover a helicopter or other vertical takeoff and landing aircraft is the addition of vertical, longitudinal, and latitudinal degrees of freedom that can be manipulated in addition to the roll, pitch, and yaw of fixed-wing aircraft. Compounding the difficulty of controlling these additional degrees of freedom is that they combine, making the effects of aircraft movement visually ambiguous. For example, when a helicopter drifts forward from a stable hover, the visual impression is of the ground moving toward the aircraft. However, if the aircraft moves straight up from a stable hover, the ground also appears to be moving toward the aircraft—ditto if the aircraft pitches up. Thus, the same visual cue can indicate any combination of three different actions.

In the OZ display (Figure 2b), each degree of freedom is both visually apparent and coordinated. Thus, the inherent visual ambiguity is removed from the task, which reduces the cognitive effort required for learning to perform the task. In an experiment to test training hover in simulators, students were trained to hover using the OZ helicopter display, then transferred to conventional instruments over 20 training sessions lasting over four weeks. The students were taught hovering in a low-end commercial simulator utilizing the OZ display and then tested in a Blackhawk simulator utilizing the standard instrument panel. The results showed significant skill at the hovering task after training using OZ, with the training successfully transferring to standard instrumentation. Indeed, the trainees' performance was indistinguishable from that of Blackhawk flight instructors.[4]

Principle 6: Relate Elements through Motion and Convergence

Because the different degrees of freedom (Principle 5) are mapped to a common frame of reference (Principle 3), the central means for relating them is through motion and convergence. In the helicopter case, the rates of movement of all six degrees of freedom are key indicators of the input required from the aircraft operator. When in a stable hover, the display (and the aircraft) will appear motionless. The beginnings of motion alert the operator that not only is input required, but also the type and magnitude of the input. They also indicate which aspect of the hover is going awry.

Similarly, the OZ fixed-wing display uses motion and convergence to enable pilots to perform standard tasks efficiently. In the simple task of descending to a specified altitude, the operator simply pitches down until the center circle (the nose ring) is directed toward the desired altitude, and then has the nose ring gradually follow the desired altitude to the horizon line. This allows fairly dramatic descents to round out and arrive at the desired altitude without overshoot. Once the aircraft has arrived at the desired altitude, the display uses convergence and divergence to convey whether the aircraft is maintaining or deviating from that altitude. If the aircraft remains at the desired altitude, the layer of stars at that altitude will appear to move horizontally across the screen, overlapping the horizon line. A significant deviation from that altitude (+/– 10 feet) will be depicted by the stars in the altitude layer splaying vertically at the edges of the screen, providing a visual alert that the aircraft has moved off altitude.

Principle 7: Minimize the Number of Display Elements but Maximize Their Utility

As discussed in Principle 1, OZ display elements are constructed so that they can efficiently use both the ambient and focal visual pathways. This requires using very simple visual perceptual primitives such as dots, lines, circles, and other simple geometric shapes. For each desired functionality, we strive to use as few display elements as possible. Because ambient vision is sensitive to differences in contrast rather than resolution, adding structures that are more complicated than four-sided objects tends to require access of the focal vision pathway to interpret. Because of this, the fewer markings and the simpler they are, the better.

In keeping with this maxim, markings on the display are often designed to support more than one function. For example, the bent wings of the OZ fixed-wing flight display have the primary task of conveying the power required for level flight at a range of airspeeds between stall and never exceed (the flight envelope). However, a secondary task is performing a standard rate turn. The bank angle required varies with airspeed, so the angle between the bent wings adjusts to portray the bank angle required for such a turn. Additionally, the shape of the bent wings can be modified to show other airspeed functions such as range, endurance, and true (versus stylized) drag.

Principle 8: Distribute the Details of the Task

Displays for performative systems should allow the operator to perform the majority of operations using ambient vision so that focal vision can be directed toward aspects of the display that convey important details for the current stage of operations. Frequently occurring aspects of the task should be represented redundantly on the display, while aspects of tasks that are infrequently performed, or are performed during only one phase of an operation, can be represented for attention during that phase and ignored outside of it.

The most obvious example of displaying redundant information is the starfield itself. No matter where the pilot looks on the display, the plane's attitude information is conveyed through star orientation and movement. Another example of this is the pitch line, which intersects the nose ring in the center of the display, but also has a smaller representation on the outboard edges of the display where they serve double duty as trim indicators (see Principle 7).

Displays for performative systems don't have to be immediately intuitive or "natural." Indeed, they have to support processes of perceptual learning and re-learning.[14] After all, many tasks are difficult, have long and steep learning curves, and require significant physical and cognitive skills. The measure of the display should be that if you do have those skills, then once you understand the display, data acquisition from it is nearly effortless. In displays for performative systems, multiple perspectives are each made explicit, as are the relations of the perspectives. Meaning is conveyed directly. But such displays can only be designed and created in the context of the tasks and goals they're intended to support.[15,16] Thus, displays that are good for supporting task performance also support learning.[3,17]

We referred earlier to the notion of reducing or eliminating mental workload, so we'll close with a cautionary tale. We know that people achieve genuine expertise only after lots of hard work on difficult problems. It would be misguided to prioritize the reduction or elimination of all forms of workload, under all circumstances—although many research programs call for precisely that. What OZ exemplifies is a path toward eliminating *needless* workload that's entirely an artifact of legacy technology, eliminating it through better design of intelligent interfaces. ■

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