ERGONOMICS IN DESIGN

The Magazine
of Human
Factors
Applications

On Convergent Technological Evolution

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Reprinted from ***Ergonomics in Design,*** January 1996, pages 22-29.

The characteristic of evolution that I advance and illustrate is the *convergence* of form in systems experiencing common evolutionary forces (see Gould, 1980, for a discussion of comparable convergence patterns in natural evolution). The technical, human factors, realm in which I wish to present convergence is that of the human-machine (computer) interface. I suggest that convergent evolution, in adopting preferential characteristics, is occurring at the human-machine interface. I propose that this happens not only for the physical structure of the workstation but for the way in which resident information is displayed. I provide one metaphor that might prove useful for common representation across many divergent systems. So,

> given that complex human-machine systems evolve and, to a large extent, evolve in ways similar to natural ecosystems,
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> and
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> given that the design of complex human-machine systems needs to be informed by this parallel in order to avoid catastrophic failures that regale the history of natural ecosystems,
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> therefore, can we demonstrate that species (i.e., specific cases of human-machine systems) converge to a common form given their subjugation to common forces?

If this characteristic could be confirmed, it would provide an important rationale for direct ecological influence on the technical design of human-machine systems. This would not be a metaphorical link but rather a direct parallel. Thus, the question extends beyond design considerations alone to the fundamental role and nature of theory in human factors itself.

Forces for Convergent Evolution

Two primary forces are directing convergent evolution at the human-machine interface. I characterize the first force as the "push" of computer technology and the second as the "pull" of inherent human information-processing capabilities. The mutual presence of these forces and their interaction are critical for the convergent process to occur. (I do not claim that these are the only forces involved. There are also economic and market forces, which, through monopoly, may either sustain a poor design or suppress a superior one.) But evolution and monopoly are anathema to each other.

The effects (push) of computer technology on society are obvious, profound, and growing. The computer is the dominant and preferred system that mediates between human and machine. Frequently, the computer itself is the machine. In developed societies, for both large-scale, complex systems and small appliances, some form of computational component is pervasive. This ubiquity of a common control medium shapes and constrains possible human-machine communication.

Because technology is natural, it is subject to much the same [evolutionary] influences that occur in nature.

As computers penetrate further into everyday existence (into realms as diverse as driving and shopping), this force gains power (compare Hancock, Dewing, and Parasuraman, 1993). This power has a codicil: The proliferation of computer systems fosters an explosion of available data. This explosion becomes a conflagration when computers can readily communicate with one another.

Without context and cognition, data are sterile. But cognition and context can be impotent in the face of such a data avalanche. Thus, data overload is a particular problem, especially in the sequence of extracting information from data and directing actions based on knowledge derived from such information. The question arises as to how to structure the interface to deal with this problem, and it is here that the second force exerts a critical influence.

The force that pulls displays toward common representational forms is inherent human-processing capabilities. Humans are basically visual and operate well in complex four-dimensional (4D) worlds. We have facile perception-action skills and do well in conditions that present such challenges. We are not so skilled in decision-making environments that require the transformation of problems and formulations of answers through formal or logical representations of things, objects, or concepts. Hutchins (1994) has suggested that the transformation of problems from the representational decision-making domain to the perceptual-motor domain make them easier to resolve. Thus, computations that can be rendered into 4D perception-action questions are much simpler than, for example, complex mathematical representations of the same problem (see illustrations in Gleick, 1988, and conceptions in object-oriented design, Booch, 1991).

The question extends beyond design considerations alone to the fundamental role and nature of theory in human factors itself.

We are hardly aware that our basic visuomotor capabilities *are* skills. Indeed, the problem of seeing is, in reality, seeing the problem! Behavioral researchers do recognize that human beings can process vast amounts of visual information and, when presented with situations that have been formatted as perceptual-motor problems, can solve them with an ease and speed that connote both desired and superior performance. Little wonder that in software design, there is a fast and growing focus on graphical representations via visual media.

Convergence of the Physical Interface

What has become rapidly obvious to human factors professionals and designers – especially given the disaster and error literature (e.g., Goldberg, 1984) – is that ever-increasing information cannot be satisfactorily represented on endless, single-function analog and alphanumeric displays. The practice of adding a new display each time a new component is developed simply does not work because it leads to an unbounded exponential growth in displays. An illustration of such a case is Figure 1 (Card, 1989).

Although at some point, one simply runs out of physical space, the real concern is that critical information resides as much in the interaction between subsystems as in the singular effects shown on unirepresentational displays. Therefore, what has happened in physical display space is that the multiple layers hidden within video display terminals (VDTs) have replaced individual, physically discrete displays.

It is possible that menuing systems and multiple display pages may lead to continuing growth in the amount of information available. However, in the electronic interface, this proliferation has been hidden. Because physical screens themselves are visible only in a limited number of locations, the configuration of workstations has begun to evolve in the same direction for systems designed to control widely different processes. Figures 2 and 3 (after Wiener, 1985) illustrate two physical workstation arrangements that show convergence, a trend supported overwhelmingly in recent Human Factors and Ergonomics Society annual meeting proceedings.

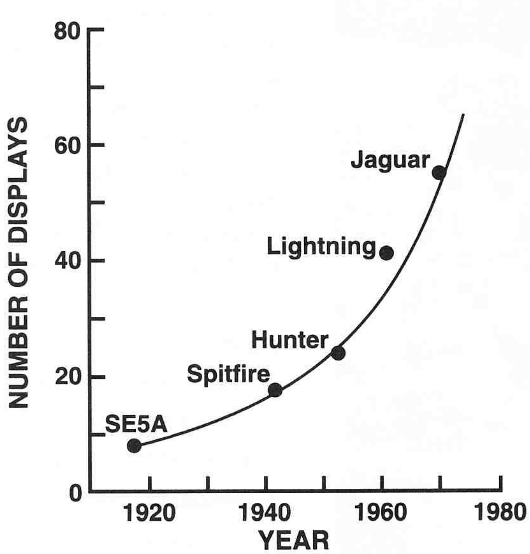

Figure 1.
Exponential increase in the number of displays in high-performance aircraft. Adapted from Card (1988).

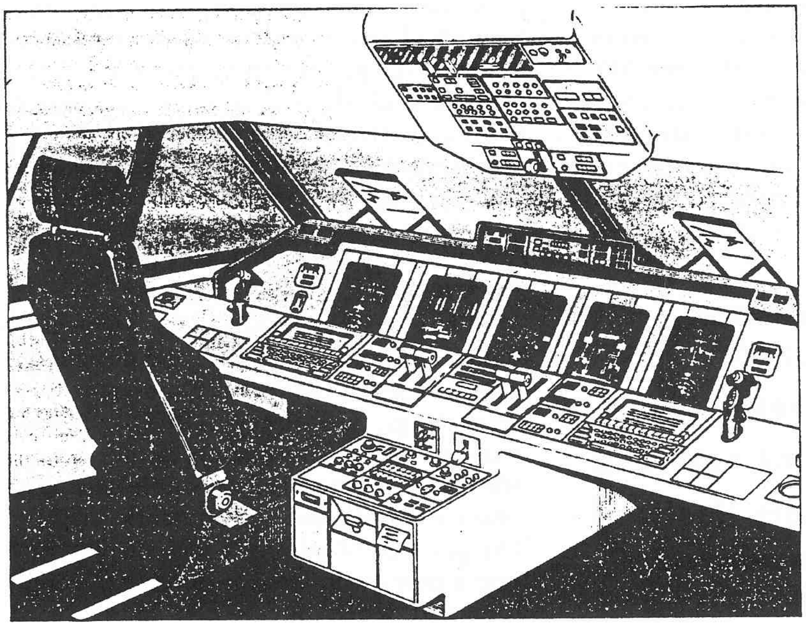

Figure 2. Artist's conception of the cockpit of the future. Courtesy of Lockheed Corporation; from Wiener (1985).

Although the workstations shown above and below share some common characteristics (despite their widely differing functions), there are some differences. Both show interaction via numerous VDTs, but their arrangement is in a single plane of display. Conversely, the more recent control room environment shown in Figure 3 depicts displays that surround the operator and are projected in a number of different planes and angles. (Before I am inundated with criticisms that previous control rooms also use this form of display arrangement, let me emphasize that my point is general and is not restricted to any single system. That is, individual systems will have differing evolutionary approaches toward a common representation, and if they discover certain characteristics in differing orders, it does not invalidate the general argument of convergence.)

In essence, then, the individual is being surrounded with information. In some contexts, these surrounding displays have few links among one another, so that almost an endless sequence of displays is presented on four walls of the control room. Note in Figure 4 (page 26) that software manipulations such as "window" techniques elaborate on this display strategy to overlay multiple representations of additional virtual physical space on a constricted actual physical space.

I emphasize here the tendency to place the individual operator, or team of operators, in an "information bubble," in which all the distal space (such as walls) is used for displays. This conception has been used to construct some virtual environments in which the "world" appears, displayed via back-projection on the four walls of the room,

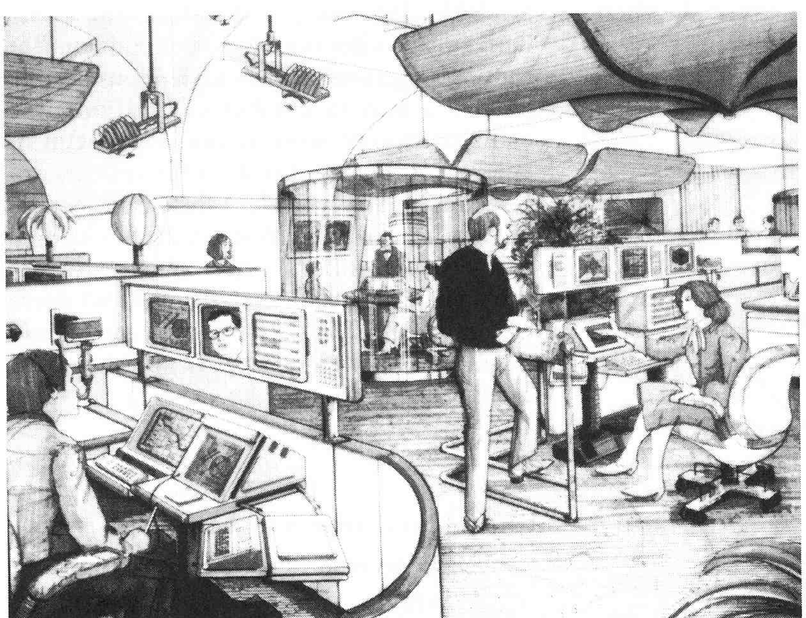

Figure 3. An office architect's concept of a future office. Courtesy of Environetics International; from Wiener (1985).

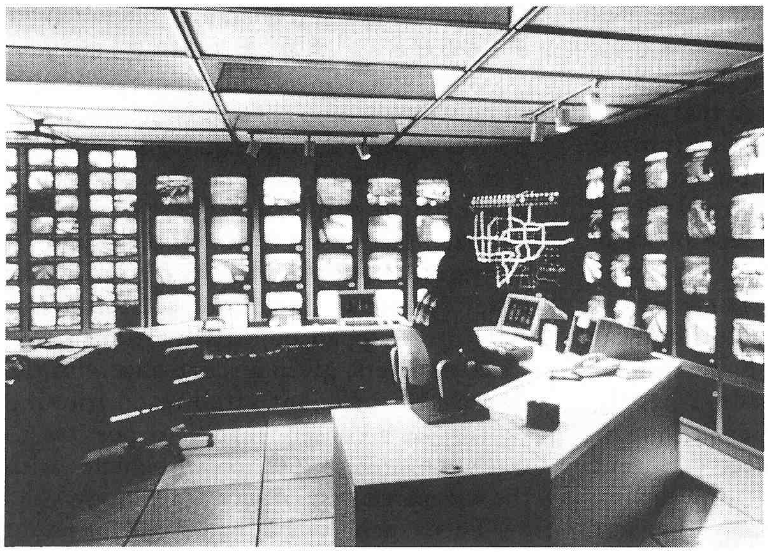

Figure 4. Illustration of an advanced traffic management and control center with multiple displays for individual highway monitor cameras.

sometimes labeled the *virtual cave* (Defanti, Sandin, and Cruz-Neira, 1993). Each of these stages of progress represents the tacit and sometimes explicit recognition that the physical interface for human-machine interaction is moving toward complete wraparound virtual representation.

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There are several ways to present virtual environments. Advanced simulation capabilities, often including actual vehicles with associated motion dynamics, have been embedded in a virtual display world. These simulation facilities – usually flight simulation – get very close to passing the Turing test for reality. The stereotypical virtual reality system is represented by eyephones and datagloves in which the individual literally wears the surrogate world. Recent attempts have been directed toward the improvement of display resolution in such systems, including advances in boom technologies in which virtual worlds are seen through movable, counterbalanced binoculars.

It is clear that some form of virtual environment is the next step along the path of the evolution of the physical interface. However, the light, fully portable, wearable virtual system is currently awaiting the development of small, lightweight, high-resolution displays. Needless to say, many commercial efforts are currently directed to the resolution of this and associated problems. But what will these future interfaces present, and will the format of information presentation converge in the same manner as the physical presentation medium?

Convergence of the Information Format

If physical workstations in diverse systems now resemble one another, what of the information itself, and how is it structured for display? Convergent evolution is not simply the widespread use of the same computer system; this might occur as a function of availability, compatibility, general affective response, or simply a common procurement procedure. In terms of information display, there has been progress toward some consensus. Alphanumeric line commands are being replaced with icon-based approaches (Shneiderman, 1983), although, as in the evolution of any system, residual and vestigial characteristics frequently remain a part of the system. Some of this progress can be seen in the comparison of differing forms of data display as presented by Jacob, Egeth, and Bevon (1976; see also Jacob, 1989) and discussed in Wickens (1984, p. 170).

Thus, there has been, and continues to be, vast growth in graphical user interfaces. It may be no coincidence that there has also been an explosive increase in the development of graphics computational power and a substantive increase in the percentage of computer-operational capability devoted to interface operation. Hence, the nature of the method of information display has itself changed to emphasize graphics ability. So it seems a logical step to propose that wrap-around, 4D representative worlds (virtual environments) promise to become the interface structure of the future. Indeed, conceptions such as the holodeck of "Star Trek: The Next Generation" fame provide 4D surrogate worlds in which immersion is achieved inside a manipulable physical space. It is an unfortunate impoverishment that such immersion is predominantly shown as replicating veridical physical spaces rather than more advanced emergent properties such as data fields – unfortunate, considering that what is displayed is not independent of how it is displayed.

The Metaphors of Representation

Displays represent systems. The important differences between systems lie in their distinct response characteristics. However, as the intermediary between human and machine, the computer can buffer many of these differences. In consequence, what is controlled might become less of an issue as *how* such control is effected moves to the fore. Eventually, might the differences between aircraft traffic control, nuclear power stations, and widespread forms of data control become virtually opaque to the operator sitting at the generic control panel viewing the generic displays? Would this be an advisable strategy? Is there any unfathomable rule that demands that there be complex displays for complex systems?

Considerable effort is being made to seek displays that present the "emergent properties" of complex systems (Moray, Lee, Vicente, Jones, and Rasmussen, 1994). However, the major question concerns the central metaphor for representation. Considering that all systems have to be navigated through some multidimensional phase space of operation, the metaphor of a boat on an ocean can capture many common elements of widespread systems operation (see Hancock and Chignell, 1995, for further details). The underlying theme of this representation, as it is in the systems themselves, is the retention of stability in the face of uncertainty and the emergent characteristic of adaptability, which is the leitmotif of life itself.

Convergence of Process: An Example

One interesting contemporary example of convergence of process concerns transportation control. Although many technologies are involved in these developments, one critical capability comes from the Global Positioning System (GPS) and its derivative, Differential GPS (DGPS). The latter system is capable of establishing a suitably equipped object's location within 15 centimeters, given a short time with the capture of sufficient satellite positioning signals. As a consequence, it is possible to track the precise location of vehicles with the widespread use of such technology.

This capability has had vastly different influences on two forms of transportation. In commercial aviation, the ability to accurately track one's own position and that of other aircraft has, among other influences, generated advocates for "free flight." In free flight, the pilot is responsible for the path of the aircraft and for avoiding other aircraft in the local airspace. The presence of GPS (and other technologies) promises to permit this goal to be achieved. As a consequence, free flight is an initiative that seeks to change the control structure from a highly centralized system to a highly distributed system, on the principle that distribution allows the best use of resources and negates the problem of information and control overload at one central control location.

> **The physical interface for human-machine interaction is moving toward complete wrap-around virtual representation.**

In ground transportation, given the current and increasing accuracy of DGPS systems, proposals have been made that, in tandem with other technologies, it may be able to provide real-time guidance. However, the issue here is that information from such systems allows the dynamic tracking of vehicles from origin to destination. In direct contrast to aviation, the proposal in ground vehicle transport, as embodied in

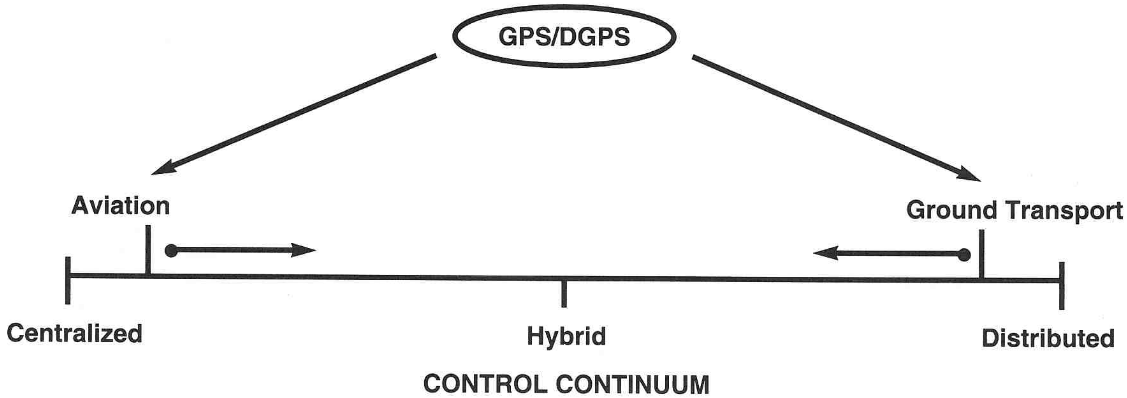

Figure 5.
Convergence of control structure in different systems under the influence of common technology.

Intelligent Travel Systems (ITS), is for greater centralized control. Thus, both of the major teams selected by the Federal Highway Administration for Phase II development of the national ITS architecture have advocated a centralized approach.

As illustrated in Figure 5, we have a common technical stimulus that, on the one hand, has generated advocates for distributed control in a current system that represents a highly centralized system. On the other hand, it has generated an equivalent interest in another system for centralized control in activities that have traditionally possessed a highly distributed structure. Two caveats are important. I am aware of the number of companion technologies that accompany position-location and positive control in both realms and have emphasized the role of GPS in the present example above some of these others. I am also aware that such technology does not affect only transport vehicles. The role of the future infantry soldier is a good example of similar effects on control structure given the dissemination of information and the sharing of control (National Research Council, 1995).

The projected development toward a wraparound information "cocoon" suggests a good, hard look at virtual reality approaches.

The central point of these observations is that each system, under the stimulus of comparable technical innovation, is converging to a form of hybrid control. In this form of control, the everyday operations are enacted under distributed control in which local operators exercise immediate decisions over their area. It is only under transient conditions (for example, bad weather or a traffic incident) that exception processing is handled more centrally. These centers exercise a monitoring and supervisory function during normal operations, but their ability to see the "big picture" enables them to deal efficiently with unusual conditions.

Not surprisingly, such forms of control are already in operation; indeed, one can follow the development of theories of brain function that have led precisely to this conception. Convergence does not have to be represented solely in physical things and objects; it can also be seen in processes.

Implications for Design

Are the foregoing observations helpful for the designer? I think they are. For those involved in designing physical interfaces, I think the projected development toward a wraparound information "cocoon" suggests a good, hard look at virtual reality approaches to represent the physical interface of the future. For the software designer, the task is to bring the critical system variables to the forefront and allow their emergent properties to become constraints and the context for a sea-lane through which the controller "pilots" the craft (system).

This conversion or transformation of complex alphanumeric and analog information into unified graphic distillations represents the software design challenge of the coming century. Although it is expected that training will still be important in developmental stages (Walker, Fisk, Phipps, and Kirlik, 1994), eventually the interface might achieve a level of transparency so that the problem becomes obvious and the solution also is then immediately apparent (Bennett and Flach, 1992; Flach and Vicente, 1989). If the interface passes the "Hancock criterion," the operator will directly "see" the task solution. More formally, if displays are homeomorphically mapped from the task domain, then the task solution becomes transparent. If displays are isomorphically mapped from the task domain, solutions may be similarly obvious, but the operator need not know what specific system is under control.

We are still some way from such representations, but I think it is important to articulate such a specific goal. For, as William of Orange once said, "No wind can be favorable for one who knows not where he's going."

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The author is grateful for the insightful criticisms of Raja Parasuraman, John Flach, and two unknown reviewers on an earlier version of this work. EID