Perceptual cognition and the design of Air Traffic Control interfaces

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ABSTRACT

Recent research in Cognitive Science provides us with new perspectives on the ways in which users perceive, think, and act in information-rich display environments This paper explores the implications of theories of spatial indexing and perceptual cognition for information visualization in air traffic control applications.

INTRODUCTION

The U.S. Federal Aviation Administration and its international counterparts are in the process of revising the hardware and software used in air traffic control. The current system relies upon a series of regional and airport controllers to establish flight paths and priorities for a large number of aircraft. The data displays that they use typically have limited graphical capabilities.

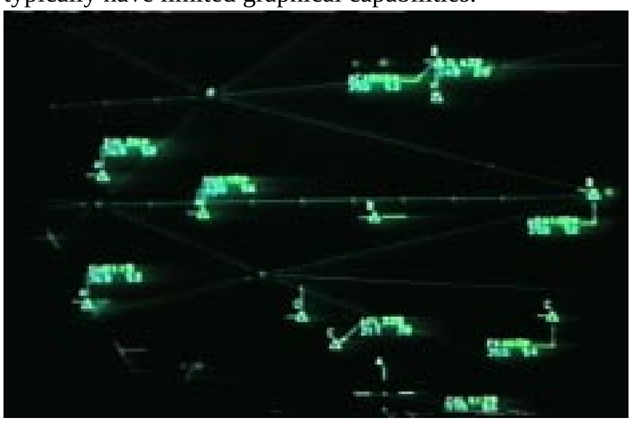

Figure 1: Current ATC display

A new approach to ATC, called “free flight” gives pilots much more freedom in choosing a flight path. Controllers are to be provided with modern graphical workstations that will allow for information visualization approaches to enable them to better understand and direct the aircraft. These include “fishtank” VR, display of protected air zones and potential conflicts, and the prediction of future locations of displayed aircraft.

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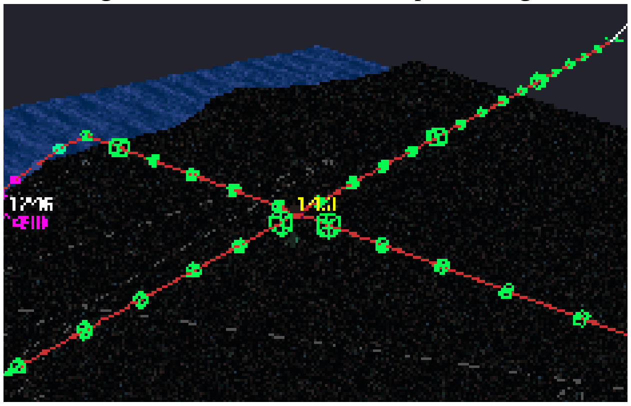

Figure 2: One proposed ATC display

Our group has been involved in supporting this effort through our collaboration with HRL Laboratories. Our focus is on applying recent theories of the cognitive architecture of human performance in complex environments. This paper reports on a part of this investigation: the application of Pylyshyn's FINST theory of indexical perception to the design of interfaces for visualizing information.

COGNITIVE ARCHITECTURE AND INFORMATION VISUALIZATION

Cognitive Architecture [1] refers to global structure of mind, as elucidated by studies measuring performance of realistic tasks in complex environments. The goal of this work is to improve our understanding of the nature of mental representations and their relationship to sensory processing.

Cognitive operations (e.g. goals, plans, schemas and scripts) are one level of the system where information flows freely between task domains. Much of our mental processing is accessible to our intuitions. We can report our pattern of thought for a protocol analysis, and may alter our mental processes by choosing to do so. Much of HCI deals with this level of the Cognitive Architecture. The traditional serial stage diagram of information processing places these operations at the "decision stage" (Figure 3).

Perceptual processing is said to occur in a set of informationally encapsulated processing modules that are instantiated in neurally isolated subsystems of the brain [2]). The modular nature of these visual routines [3] results in restrictions of the flow of information to and from them. In particular, modular sensory processes are *cognitively impenetrable*[4]-- that is to say that their representations and much of their operation is unaffected by our beliefs, plans, and conscious processes.

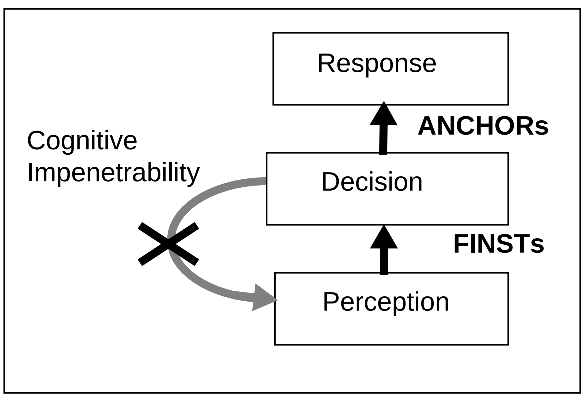

Figure 3: Sensory processing modules

In Figure 3, information flows from a data-driven perception stage to cognitive processing (decision stage), and finally to a response. This is a typical 3 stage model of human information processing found in many textbooks. We have made several modifications after Pylyshyn [5]. First, the inability of the observer to alter the contents of perceptual processing through their beliefs or effort of will (i.e. cognitive impenetrability) is depicted by the crossed-out arrow on the left. Second, the communication between the perceptual and decision stages is hypothesized to be mediated by a set of attentional tokens called FINSTs, which are described in the next section. Similarly, motor performance is shown to involve a similar mediating mechanism called an ANCHOR [6] that is beyond the scope of this paper.

PARSING COMPLEX DISPLAYS

In a complex environment, multiple perceptual objects and events must be individuated. Object characteristics must be parsed from the environment in parallel, and correctly assigned to a mental "placemarker' for the event.that gave rise to them. As object characteristics may change over time, an effective mental representation must include an object-bound memory component (called an "object file" [7]).

SPATIAL INDEXING AND COGNITION

The minimal mechanism for linking perceptual and cognitive levels of processing is a set of spatial indices or attentional tokens. These tokens (called FINSTs, for "Fingers of INSTantiation) were first utilized in computer vision applications by Pylyshyn, Elcock, Marmor, and Sander [8]. They have subsequently been found to link human mental operations (from simple visual routines, e.g. the Gestalt principle of collinearity to more complex conceptual structures) and individual perceptual events in a variety of task domains [9].

According to the FINST hypothesis, there are a limited number of these attentional tokens; this limit constitutes a fundamental bottleneck in human processing. Just as short-term memory limitations (i.e. 7 ± 2 items [10]) and focal attention (i.e. a single "spotlight" of attention) limit our ability to perform certain tasks, the availability of spatial indices can be a determining factor in our ability to parse complex displays. This bottleneck results in three levels of cognitive access to items in a complex display:

- Attended items-- Items that occur in a spatially contiguous region that the operator is currently attending to. Processing in this region follows the traditional "spotlight" metaphor of endogenous attention, where the speed and accuracy of processing (grossly defined) varies inversely with the size of the area attended.

- Indexed items-- Up to six display items can be individuated and indexed by having a FINST assigned to them. FINSTs are usually assigned in a data-driven manner based upon salient events such as the onset of a new item. FINSTed items gain several known processing advantages: They are available (potentially in parallel) as arguments for simple perceptual routines such as collinearity, conjunctive search, subitizing (rapidly counting small quantities), and speeded selection for attentive processing. FINSTed items generate unique mental representations called object files [7] that allow multiple characteristics (i.e. perceptual features) to be monitored in parallel and maintained through time as an object-bound history in short-term memory. Unlike attended items, FINSTed items can be distributed across the screen in any configuration (i.e. they do not need to fall within a contiguous region to receive enhanced processing) without losing their processing advantages.

- Background items-- The remainder of the display receives very limited processing. New items that appear at unindexed locations may attract an index if their onset is salient; however if onset occurs during a saccade or a screen blink the item itself is unlikely to be noticed [11]. Changes in these objects are likely to go unnoticed, and will in all cases be responded to more slowly than FINSTed items. Similarly, attending to these items is slower than attending FINSTed items, and the time to fixate attention onto these items increases with distance from the current focus of attention (described as attentional scanning, [12] or shifts in attentional gradients).

In tests with human subjects, display items that are FINSTed have the potential to be accessed and acted upon by cognitive processes in parallel, with higher priority than unFINSTed items. We use this model to predict the interaction of dynamic display events and cognitive processes, and to design displays that are optimized for the particular mental processes [13, 14].

A concentration on the nature of the linkages between perceptual events and cognitive structures substantially alters the way we think about mental representations. Given this mechanism, we can derive models of information processing that rely upon the perceptual world to provide much of its own representation [13]. The theoretical issues involved are beyond the scope of this paper, but a forthcoming book by Pylyshyn (to be published by Ablex) should provide sufficient background for interested readers.

APPLICATION TO THE ATC INTERFACE

If our theories are correct, they should help us to design visualizations that are tailored to support the way in which we process, think about, and remember events in complex scenes. We can then extrapolate from our theories to generate some design recommendations:

Ideally, the number of salient display items (e.g. aircraft) should be kept small, to avoid exceeding the number of FINSTs available (approximately 6). This would insure that each display item would maintain its individual object-history representation, and that changes in its display characteristics would be noticed quickly. Since the number of aircraft displayed will typically exceed the number of FINSTs, they can be perceptually grouped into sets through a synchronous salient display change, ideally their simultaneous onset.

Second, the cognitive classification of interactions between aircraft should be coded as arguments to known visual routines, such as Gestalt grouping. An example of this is the current practice of spacing aircraft at equal distances along a flight path to a runway. Not only does this serve to minimize the potential for conflict, but it has the added advantage of perceptually grouping the aircraft as a single unit, i.e. an approach vector.

Third, if continuity of processing is important, we must avoid display transformations that disrupt the ability of FINSTs to “stick” to their object-- indexed items should move smoothly to new positions rather than abruptly shifting location. In the current static view radar display this is a natural outcome of the smooth changes in the flight path of passenger aircraft. In the proposed fishtank display, however, the ability to zoom and rotate the images may violate this constraint.

The onset of visualization cues for tactical and protected air space surrounding aircraft in the proposed ATC interfaces (Figure 4) may have the unintended effect of “stealing” FINSTs from nearby aircraft, reducing their salience and possibly causing the operator to lose track of their history. This can be avoided through the use of perceptual changes that are less likely to draw a FINST, such as colour change or slow onset.

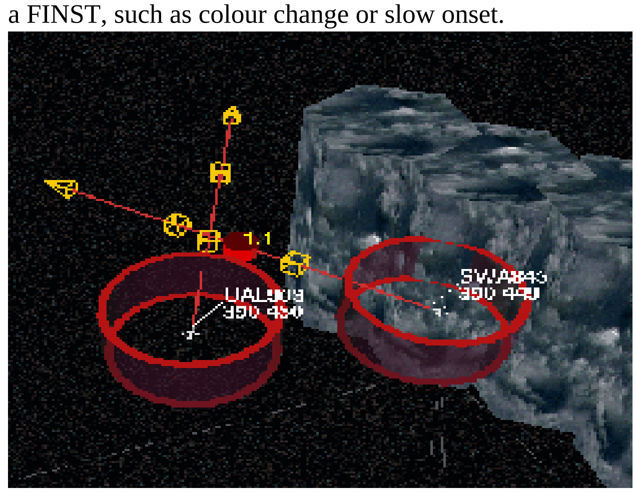

Figure 4: Display of Protected Air Zones

UNANSWERED QUESTIONS.

A fundamental question that we are investigating is the ability of FINSTs to survive global transformation of display spaces, such as rotation in depth.

Other aspects of the research deals with the impact of the display changes that we suggest upon performance in the ATC context. While the perceptual effects we are examining have been validated in the laboratory, their impact on the tasks and situations that are encountered by controllers remains to be determined.

INTERFACE TESTING APPROACH

The general approach we are taking relies on the isolation of key aspects of the display environment, comparing FINST-friendly vs. FINST-hostile information visualization approaches in a sequence of increasingly frequent display events. By reducing the interval between events, we can examine the extent to which the increased cognitive processing that should accompany the FINST-hostile displays contributes to a breakdown in processing and the inability of test subjects to deal with the rapid event sequence.

As much as possible, events will be taken from critical incident records collected by the FAA and related organizations. The support of HRL and Raytheon Canada has been instrumental in giving us access to task information, and will hopefully aid us in contacting experience controllers for additional information on their experiences and approach to their task environment.

WHAT WILL OUR INTERFACE ACCOMPLISH?

Our hope is that our work will contribute to the design of more effective approaches to ATC. In particular, we hope to insure that the new display technologies and techniques do not create new difficulties for controllers based upon the interactions of display events, spatial indices and the visual routines that process them. In addition, we hope to aid developers to support the new free-flight protocol, where the predictability of flight paths is less than the current controller-centered model. Care must be given to the presentation of exceptions, such as private pilots who may wander into protected airspace inadvertently, and older aircraft that may not communicate data as effectively as more current models.

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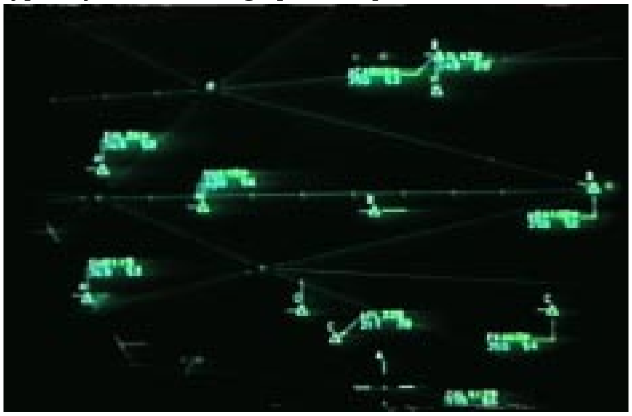

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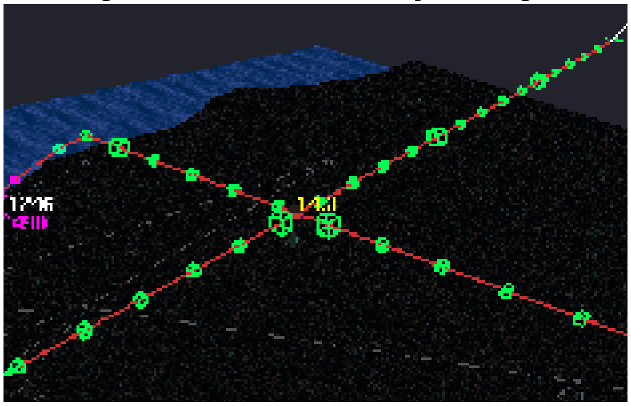

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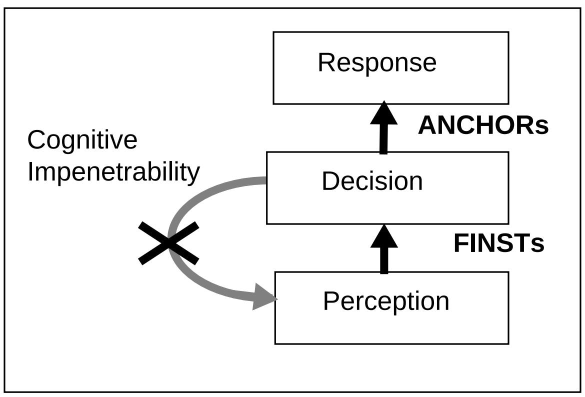

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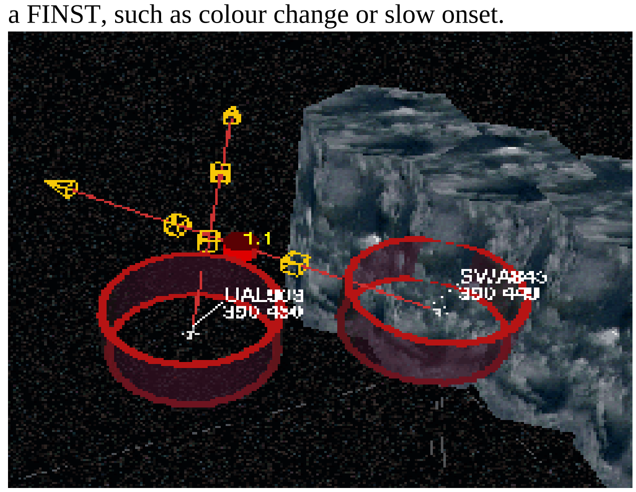

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