Abstraction, Integration, and Organization of Information: Case Study and Design Approach

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> "The word information, in this theory, is used in a special sense that must not be confused with its ordinary usage. In particular, information must not be confused with meaning. In fact, two messages, one of which is heavily loaded with meaning and the other of which is purely nonsense, can be exactly equivalent, from the present viewpoint, as regards to information. It is this, undoubtedly, that Shannon [16] means when he says that 'the semantic aspects of communication are irrelevant to the engineering aspects.' But this does not mean that the engineering aspects are necessarily irrelevant to the semantic aspects."
>
> Warren Weaver, 1949. *Recent Contributions to the Mathematical Theory of Communication*, p. 99 [18].

ABSTRACT

In this paper we discuss a general approach and several methods for abstracting data into information and then integrating and organizing it for the purpose of display. Two methods for abstraction are discussed: (1) abstraction by re-arrangement (of geometric structures) and (2) abstraction by statistical patterns. We then focus our attention on several heuristic methods for compacting large amounts of information for display. Two examples are provided, the abstracted Diagram of the London Underground and a graphical display for identification of anomalies in pilot automation interaction. We discuss these two examples in the context of a general framework for extracting signals, abstracting data, integrating information, and organizing structures of information into a whole.

Keywords

Data, Abstraction, Integration, Organization, Presentation.

INTRODUCTION

Modern information systems, such as networks, database systems, and decision support systems, contain and provide extensive volumes of data that is available for analysis and display. In aerospace applications, for example, sensor information about the state of the craft is vital as the pilots and astronauts are isolated and removed from the working of the machine. With the introduction of Integrated Vehicle Health Monitoring (IVHM) technology, there will be even wider sensor coverage available, allowing for almost real-time computations of expected (i.e., learned) values and relating them to observed values, computations of trends, and generation of composites of variables. In the distant future, it is foreseeable that with nanotechnology almost all components, even down to bolts and nuts, will transmit their state, making them available for computation and display. This will not be limited to hardware and software, and inevitably will also include physiological and psychological information (about astronauts on long-duration missions, for example).

Yet the question of how to provide this wealth of data and information—so as to aid users in the process of monitoring, analysis, decision making, considering consequences, and, ultimately, taking the appropriate action—is a tough one to answer. Given the limited display "real estate," current methods of information presentation (the "one sensor-one indicator" approach and segmentation of information into multiple screens), it is foreseeable that user interfaces will become the bottleneck of information flow, thus hindering our ability to fully understand the behavior of information systems and use them safely and efficiently. Since the amount of data that is available for computation and display is bound to increase in the future, this key problem deserves a thorough theoretical and methodological consideration.

For information to be represented and presented in a way such that it is well understood and can be safely and efficiently employed by users, it must create order—that is, an organized way by which cues and signals (of the environment and the system under consideration) are extracted, computed, and presented to the user. Order must be there to preserve the underlying structure of the information and make sure that it supports the user in performing his or her task within the real-world context. The result is better understanding and awareness, which allows users to identify patterns and relationships that otherwise are hidden and masked. Yet the term "order"—which is used informally by artists, architects, and scientists—is quite difficult to define and pinpoint [1,2].

A Conceptual Framework

To understand this intricate topic of order for the purpose of creating user interfaces for information systems, we need first to get to the root of it; to its source. To this end, consider the pyramid in Figure 1. It has four levels: (1) *extraction* of signals from the system and its environment and turning them into data; (2) *abstraction* of data into information; (3) *integration* of information into geometrically coherent structures so as to show meaningful relationships, supporting knowledge and understanding; and (4) *organization* of these information structures in order to create order and a sense of wholeness.

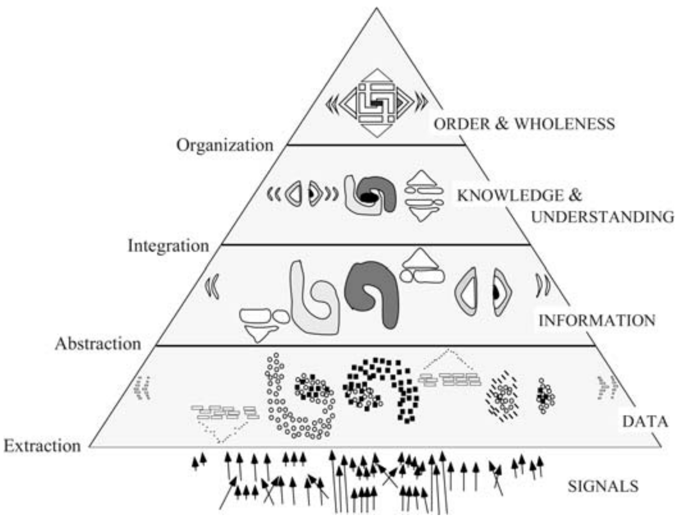

Figure 1. *From signals to organization of information*

(1) With respect to extraction of signals, the environment and/or the technological system under study emits multitudes of observables or measurables. Some of these measurables (such as electromagnetic or thermodynamic signals) are sensed and hence become, for us, data with a certain spectrum and range signature. Some, in the case of software, are cues that the system sends about its behavior. These signals and cues are collected and transformed and then become available for manipulation, computation, analysis, and, eventually, display. It is important to mention here that not *all* measurables are extracted so as to become signals (or cues, in the case of software). Likewise, not all attributes of the sensed signals can necessarily be employed as meaningful data. This is important when it comes to analysis, to diagnosis, and to decision making, because frequently the available data about a system are only a partial description of all that is going on. In the final analysis it is the relationship between the signals emitted and the user's eventual action selection that really matters [8]. The better we understand this relationship and the better job we do of collecting the "important" signals and cues and placing sensors at the right places, the more successful is the overall operation.

(2) Data, we argue, are not necessarily information. For any data to become information they must be "meaningful." One approach to this transformation from data to information is Gregory Bateson's assertion that "the elementary unit of information is a difference which makes a difference" (see [4] Part V, Chapter 5). So for example, the fact that the temperature in a room ever slowly fluctuates around 72 degrees Fahrenheit is certainly a difference (±1 degree), but it makes no difference (and is of little immediate consequence) to the person giving a lecture in the room. However, if the temperature in the air conditioning ducts has reached 110 degrees and the room is warming up rapidly, then this is a difference which makes quite a difference—because the audience is bound to evacuate the room shortly. Fluctuations of ±1 degree around 72 degrees are only data; an increase of 38 degrees is information. The point is that information is a quantitative difference (+38 degrees) that also makes a qualitative difference (audience will evacuate). Finally, it is important to recognize, that qualitative differences are dependent upon the situation and context, may change with time, and differ from one person to another (e.g., "one person's trash is another's treasure").

User interfaces are always an abstract description of the underlying system. At the basis of every user interface is a determination and classification of which data are not important for the user (and can be suppressed) and which are meaningful (and should be provided). The main issue here is the role and function of the interface and the kind of communication it "builds" with the user within context.

Generally speaking, there are many forms of interface abstractions: e.g., abstraction by elimination (suppression of signals), abstraction by rearrangement (of geometrical structures as in abstract subway maps), abstraction by shapes (as in configural or radar displays), abstraction by statistics (e.g., mean and standard deviation as a representation of a distribution), abstraction by clustering, and more. What is common to all forms of abstraction is that since the output of the abstraction process defines the information content of the interface (from which the graphical user interface is then developed), great care must be taken to create and maintain the "mapping function" between the input and output of the abstraction process.

(3) The third level in the pyramid of Figure 1 is integration of information. For information to be useful beyond being a mere collection of individual pieces of information (e.g., room temperature, humidity, lighting level, etc.), it must be integrated and linked. We must always remember that the user is physically isolated from the system under consideration and has no other means to sense and understand the situation. Furthermore, with automation, the user is commonly only monitoring the system and therefore mentally isolated from the control aspect ("out of the loop") [13]. Since modern information systems are complex and have multiple interacting relationships, we strive to show these relationships (e.g., cause and effect, correlation, side effects, conformation and voting schemes of multiple computers) to the user to foster better understanding and awareness of the system and its environment. Creating geometrical forms and structures to convey these relationships takes place at this level in the development of the interface.

The last level (4) is concerned with the organization of the information to create an holistic "world view" for the user. Only then does it become possible to take in the full meaning of the intricate details (e.g., zooming in and out, exploring relationships, abstraction and refinement). When operating from this wholeness perspective, free of distraction and preset confinements, the direction and action to be taken become clear, strong, and effective. Eventually, if this organization is indeed successful, the user should not view himself or herself as removed and isolated from the system and the environment, but rather as inseparable from it; just like a race car driver, who in the midst of action, is unable to determine where his limbs end and where the car begins.

The Framework in Context

To anchor the above theoretical discussion within an operational context, consider the emergency landing of an Air Transat Airbus A330-200 aircraft. The twin engine airliner, bound from Toronto to Lisbon Portugal on August 23 2001, lost a considerable amount of fuel while flying over the Atlantic due to a fuel leak. In response, the crew diverted the aircraft toward the island of Terceira in the Azores. Within 25 minutes of the diversion, the right engine quit; shortly after, the left engine quit as well. The crew piloted the crippled aircraft for 19 minutes, gliding without power for some 65 nautical miles, and made a safe landing at Lajes airport [9].

The fuel leak was caused by a rupture in the high-pressure fuel line on the right engine, which failed as a result of hard contact with an adjacent flexible hydraulic line. The reason for the hard contact (during installation and compounded by in-flight vibration and pulsation of hydraulic fluid in the line) was a part mismatch between the fuel line and the hydraulic line, each belonging to a different version (mod) of the engine. The parts were erroneously installed by Air Transat technicians several days before the flight and the mismatch was not detected during a quality control inspection.

Analysis of the incident revealed some serious shortcomings in the way information is presented in modern aircraft, design and use of procedures, and subsequent crew actions. What in particular interests us here is the information that was available to the crew about the unfolding situation through their systems displays, how it was presented, and its relation to crew actions. We shall discuss this in the context of the pyramid from Figure 1.

The leak began 3 hours and 46 minutes into the flight. There was no direct or even related cockpit indication for this kind of fuel leak problem. Twenty-five minutes later, the crew observed unusual engine oil indications on the right engine: Oil temperature was low (about half that seen on the other engine), oil pressure was high (almost twice that expected), and oil quantity was relatively low. The crew had no knowledge as to the meaning of these indications and there was no reference to such abnormal indications in the aircraft manuals. They contacted Air Transat's maintenance control center in Montreal, but technicians there could also not find any reference to the meaning of the problematic indications. Hence the indications, albeit abnormal, were operationally meaningless to the crew (abstraction – from DATA to INFORMATION). After watching the indication for sometime and trying to develop an hypothesis, the captain believed that the unexplained combination of abnormal values reflected a "computer error" (sensor error).

In retrospect, the abnormal oil indications were in fact related to the fuel leak: As cold fuel arrives from the wing tank it is warmed by the hot engine oil, which in return cools off the engine oil. This heat transfer takes place in the fuel/oil heat exchanger unit, located downstream of where the leak occurred. The gush of fuel into the exchange unit overcooled the oil. It also increased the viscosity of the oil, which resulted in higher oil pressure. Finally, the slower movement of the high-viscosity oil circulating in the system resulted in lower quantity of measured oil in the reservoir. This relationship between the oil and the fuel system is not portrayed on the displays; each system is displayed on a separate screen page (integration – from INFORMATION to KNOWLEDGE).

Thirty minutes later, the Engine Electronic Centralized Aircraft Warning System (ECAM) advised the crew of a developing fuel imbalance between the right and left fuel tanks (each one separately supplying fuel to its respective engine). Fuel imbalance hints at some kind of difference between the fuel consumption of the two engines or a leak in the fuel tanks. To correct the imbalance (of more fuel on the left-wing than on the right-wing tank), the crew opened the cross-feed valve and turned the right-wing fuel pumps off in order to feed the right engine from the left-wing tanks. By doing this they further depleted the remaining fuel in the aircraft by sending precious fuel from the left side to the leaking engine.

The crew later stated that because there were no other signs of fuel loss (engine fuel flow parameters and other engine indications were normal), other than lower than expected overall quantity of fuel onboard, they still believed the problem was "computer error." Since the quantity of fuel in the tanks constantly decreases as the flight progresses and is a function of the amount of fuel loaded, there is nothing to aid the crew in anticipating what are "normal' values at any given moment (short of manually computing these values). A related factor is *fully* automatic transfer of fuel between tanks (so as to constantly adjust the center of gravity of the aircraft) which takes place at various time periods during the flight. Current displays do not provide any integrated information, such as fuel consumption rate, comparison between the current fuel level vs. expected fuel level over time, or computation of fuel on board vs. fuel used in relation to the amount of fuel initially loaded (integration – from INFORMATION to KNOWLEDGE). As a result, the crew was required to manually calculate the rate of fuel loss, and search elsewhere for additional or missing information, tasks which are both demanding and time consuming.

Throughout this period, the crew focused their attention on the abnormal engine indication, believing that their major problem was the engine, the fuel being only secondary. They also continued to believe that these indications were somehow all related to a computer error. Because system-related information is organized in modern cockpits by means of a single screen with several embedded pages that need to be selected for display (e.g., engine, fuel, hydraulic, wheels, etc.), the need to constantly switch between pages may have robbed the crew of the capacity to consider the health of the aircraft as a whole (organization – from KNOWLEDGE to WHOLENESS)

With the cross-feed valve open, the fuel leak inside the right engine caused fuel from both tanks to be sprayed into the air. Since it was the middle of the night, the spray of fuel, which is visible during daylight, went unnoticed. The aircraft was leaking fuel at an alarming rate of about six tons per hour. Eventually, the tanks ran dry and the right engine stopped working, shortly followed by the left engine. The aircraft became a glider. The crew used exceptional piloting skills and made a safe approach and landing. Two passengers received serious injuries and thirteen cabin-crew members received minor injuries during the emergency evacuation via the aircraft's chutes. The aircraft suffered structural damage to the fuselage and to the main landing gear.

It is important to note that while reading such incident reports, we tend to forget—since we already know the cause, problem, and outcome—that the flight crew, operating under extreme stress, were confronted with multiple indications that did not lead to any single conclusion and had to ascertain dozens of different hypotheses as to what was really going on. All of this while still piloting a troubled aircraft, planning and executing a diversion, and getting ready for the possibility of ditching the aircraft in the midst of the ocean. This, again, highlights the importance of having a well-organized world view of the aircraft systems vis-à-vis the state of the environment.

The task of presenting information in an appropriate way is not an easy one. In fact, we are currently very limited in our ability to do this job for large and complex information systems. The current information presentation approach of "one sensor-one indicator," "one (sub) system-one screen page," and the reliance on alarms presets is beginning to fail us. Likewise, the "management by exception" automation philosophy employed in the design of the fuel system of the Air Transat aircraft may be problematic. In this approach, the automation is allowed to initiate and perform actions on its own, requiring relatively little explicit and observable human-machine interaction. But the approach imposes extra monitoring demands if there is a problem and involves the risk of losing system and mode awareness. In the case of the Air Transat this problem manifested itself in two ways: The sudden and unexpected presentation of apparently anomalous and incredulous information, and presentation of the system abnormal state in a way that did not readily lead the crew to identify and rectify the problem.

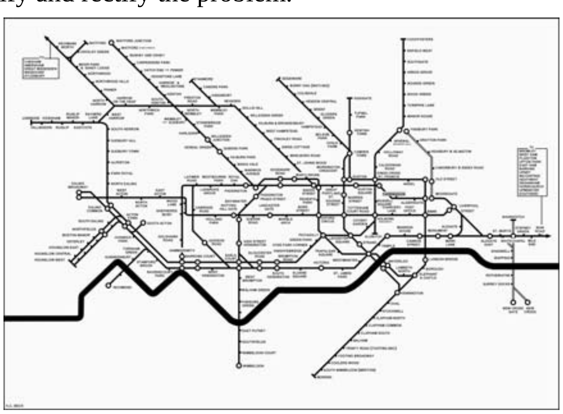

Figure 2. *Diagram of the London Underground*

The challenge is for automation to not merely provide data but to reduce the cognitive effort by helping users to locate, integrate, and interpret those data in a meaningful way. The only problem is that we still do not know how to design automation accordingly, nor do we fully understand the relationship between information presentation and automation. In that respect, we currently view the problem of human-automation interaction, which has been at the forefront of our research for many years, as a subset of the larger issue of information representation and presentation [13].

Outline and Scope

What follows are two examples where we begin to consider principles of abstraction, integration, and organization. The first example is a brief analysis of the well-known London Underground Diagram in order to uncover some of the principles that make it so successful. The second example concerns construction of a statistical graph for identifying patterns of pilot interaction with the automated flight control system of a Boeing 757/767. The proposed presentation allows for identification of anomalies (i.e., deviations from the norm that can potentially lead to an incident or accident) in the way pilots respond to the environment and interact with the aircraft's flight control system. We describe the data and representation of statistical patterns, and show the process of the design. We conclude with several observations about data abstraction, information integration, and organization of geometrical structures for the purpose of display.

TALE OF TWO MAPS

Figure 2 is a map of the Underground train system in London, circa 1933. Since then, tracks have been added, stations opened, and stations closed—but the abstract and clean graphical format has not changed much. The purpose of the Underground diagram is to help travelers navigate their way between stations—moving from one point to another and switching lines at various interconnecting stations. Figure 3 is the actual, geographical, map of the Underground [12]. Here you can see all the twists and turns of the train tracks and the real curves of the Thames River.

Figure 3. *Geographical map of the Underground*

In 1933, the official (geographical) map of the Underground of Figure 3 was replaced with the abstracted map of Figure 2. The reason for the switch in display format was economic. In the late 20s and early 30s, London Transport, which operates the Underground, was losing money. Survey after survey demonstrated that occasional passengers and even commuters had a hard time using and navigating their way with the geographical map; it was "too confusing." When the abstracted description was introduced in 1933, it was a big hit with both Londoners and tourists, because it catered to the user's information needs—not to the geographical details. The map was quickly nicknamed "the Diagram," primarily because it resembled an electrical wiring diagram. This was no coincidence, as Mr. Harry Beck, the originator and designer of the abstracted diagram, was an electrical draftsman for London Transport. He took on the problem of redesigning the map as a personal side project [7].

Abstraction, Integration, and Organization

To further appreciate the ingenuity of the London Underground diagram we will consider and analyze it along the lines of the pyramid discussed earlier. As for the notion of abstraction, one immediate observation is the creation of an aperiodic grid, running vertically, horizontally, and diagonally (45°), to which all of the lines adhere. The formation of this repetitive grid, which gets the rhythm going and serves to unite the space, is an important characteristic of any profound object in art and architecture (see [2] Chapter 15).

One of Beck's major efforts in creating the diagram was the alignment of stations along the grid and in particular with respect to interchange stations (that is, stations that have more than one line running through them). This process of integration consumed much of Beck's follow-up work, as well as that of his successors at the London Transport design bureau. The *Aldgate Triangle*, a complex of several stations, including the *Bank* and *Monument* stations that are connected through an escalator, is an example of an area that received much attention in various redesigns. Figure 4 is a sketch by Harry Beck from 1965, showing four different solutions for this difficult integration problem.

Beck's ingenuity is also seen in the way the map is organized. Since he needed much space and clarity in working the details of how to integrate the lines with the interchange stations (mostly in the downtown area), he made the map nonlinear: The central area in downtown London is enlarged, while the suburb areas are compressed. The distortion makes it easy to see the details of the (interchange) stations and lines in the downtown area. In the suburbs, were there is usually only one line, he safely compressed the distances between the stations and was less concerned about the geographical distortion.

The London underground diagram is considered one of the graphical marvels of the 20th century, and this particular abstraction format has been maintained and is also used by all subway systems of the world: New York, Boston, St. Petersburg, Tokyo, Sydney, and Athens. In retrospect, Beck's general approach for packing information into a relatively small diagram paid well over the years. His organization scheme for the London Underground turned to be flexible enough to accommodate most effectively all the new stations and lines that were added since the diagram's inception (Figure 5). It will probably continue well into the 21st century, as it currently supports the prototype of the future diagram which includes several additional lines.

In conclusion, we argue that every interface, from pocket-held subway diagrams to complex avionics displays, is always an abstracted description of the underlying system. This abstraction is a must—otherwise the user would be subjected to enormous, and mostly irrelevant, amounts of information. As such, an important and fundamental aspect of interface design involves an intricate process of abstracting data so as to suppress what is irrelevant and retain what is important. From this perspective, the designer's goal is to strike a fine balance between providing insufficient information and providing superfluous information. Specifically, when insufficient information is provided to the user, he or she may not be able to perform the specified task correctly. While the problem of information insufficiency can, when identified, be clearly communicated and shown [6,14], the problem of identifying when information is superfluous is less crisp and more difficult to pinpoint. Nevertheless, when the interface is overly complex and redundant, people can easily get confused, frustrated, and may end up not performing the task at all [17]. See [10] for a formal method approach for generating interfaces that are sufficient and also succinct.

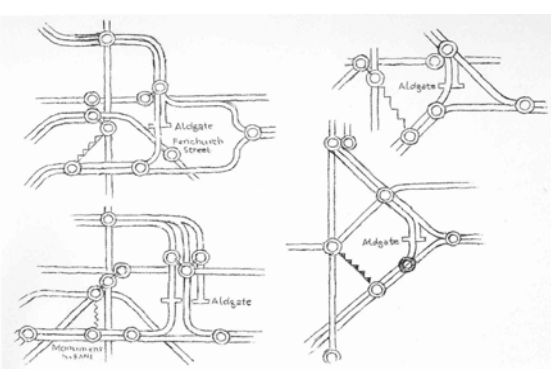

Figure 4. *The "Aldgate Triangle" (adopted and reprinted from [7] with permission)*

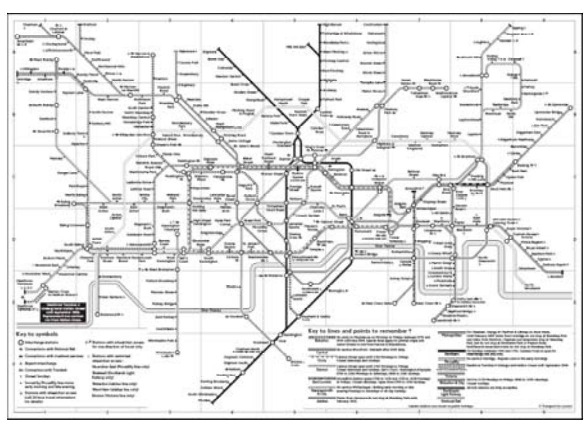

Figure 5. The current (2006) Underground Diagram

PILOT-AUTOPILOT INTERACTION

In this section we describe the operational environment in the study and the kind of data that was collected. We then go on to describe how the data was abstracted using canonical correlation analysis and the kind of patterns that emerged. The last two subsections discuss the geometrical organization of the patterns into a whole, ways to compact information, and several properties of information integration.

Operational Environment and Data

The data come from a study of crew interaction with the automatic flight control system of the Boeing 757/767 aircraft. Sixty flights between six city pairs were observed during regular revenue flights. During these cockpit observations, every visible change in the aircraft control modes, either manually initiated (e.g., the pilot selected a new mode) or automatically initiated (e.g., an automatic mode transition), along with each setting relating to the flight control system status (e.g., waypoints and altitude values selected by the pilot) was recorded. Likewise, every visible change in the operational environment (e.g., a new instruction from Air Traffic Control, or switching from one Air Traffic Control facility to another) was recorded, along with related variables such as the aircraft altitude, speed, and distance from the airport. In a way, it was like taking a snapshot of every change that took place both in and outside the cockpit. Overall, the dataset consisted of 1665 such snapshots, each characterized by 75 variables. Approximately half of the variables had to do with the operational environment and the other half had to do with pilot's responses [5].

In general, we were interested in identifying the relationships that exist between the state of the operating environment (considered as the independent variables—X's) and pilots' actions and responses as represented through their interaction with the automatic flight control system and its modes and settings (dependent variables—Y's). The data, abstraction methods, and resulting diagrammatic format described here were used for a post-hoc analysis. Nevertheless, with increased automation and better sensor coverage and communication bandwidth, it is conceivable that in the near future on-line monitoring will begin to take place (and be available for display at the airline's maintenance control center, for example).

Abstraction and Representation of Statistical Patterns

Canonical correlation analysis is a type of multivariate linear statistical analysis, first described by Hotelling [11]. It is used in a wide range of disciplines to analyze the relationships between multiple independent and dependent variables. The value of using canonical correlation is derived from its unique suitability for finding independent pairs of correlated patterns.

Canonical correlation analysis computes two derived (or "canonical") variables, X and Y, such that the correlation between X and Y is as large as possible. X is a weighted average of the independent variables, and Y is a weighted average of the dependent variables. The computation reveals several such relations between independent and dependent variables, each indicating a distinct pattern set that exists in the data. Each of these pattern sets can then be reduced to a bivariate correlation, which is visually inspected using a familiar bivariate scatter diagram. By using the scatter diagram it is possible to focus attention on correlation outliers which fail to conform to the dominant patterns (e.g., crews using an inappropriate vertical mode during the last phase of the approach, or any other departure from normal operations). During the observational study, 22 such departures were noted and recorded. Most of them showed up as outliers on the bivariate plots (see [5] for more details of this issue).

Traditionally, the results of canonical correlation analysis are presented by means of numerical tables. However, a tabular format hinders the eye from recognizing and understanding the multidimensional patterns that exist in the data. Yet these patterns are extremely important, not only because they help the analyst characterize the most important environmental conditions and their corresponding effects on pilots' actions, but also because this method can reveal deviations from a well-established pattern (which may be indicative of an operational error that can potentially lead to an incident or accident). Using structured correlations (the correlations of the X canonical variate with each of the original independent variables, and of the Y canonical variate with each of the original dependent variables), but seeking to avoid tabular representation of the data, we organized the variables along a sunburst representation where all the independent variables (X1, X2, …) are on the right side of the circle, and all the dependent variables (Y1, Y2, …) are on the left [15]. We specifically chose a circular structure to emphasize that "all variables are equal" (whereas employing a vertical and/or horizontal layout implicitly suggests some ordering).

The canonical correlation analysis identified four sets of patterns that were statistically significant ($r = 0.95, 0.88, 0.81, 0.72$; $p<0.001$) and independent of each other. Figure 6 shows the first set ($r = 0.95$), containing two patterns—one positive and one negative—depicted by dark and white bars respectively. For example, the positive pattern (dark bars) in Figure 6 indicates that for all independent variables (X's) *when*

- altitude is high (above the average of 13,000 feet),
- the phase of flight is "descent,"
- the Air Traffic Control facility is "approach control,"
- and the vertical clearance is "descend to altitude,"

then the corresponding modes and settings selected by the pilots are most likely to be:

- autopilot "engaged,"
- pitch mode in "flight level change,"
- and thrust mode in "cruise."

The reciprocal pattern (white bars) indicates that *when*

- the Air Traffic Control facility is "departure control,"
- and the vertical clearance is "climb to altitude,"

Then the most likely mode/settings selected by pilots will be:

- autothrottles "engaged,"
- pitch mode in "vertical navigation."
- and thrust mode in" climb 2."

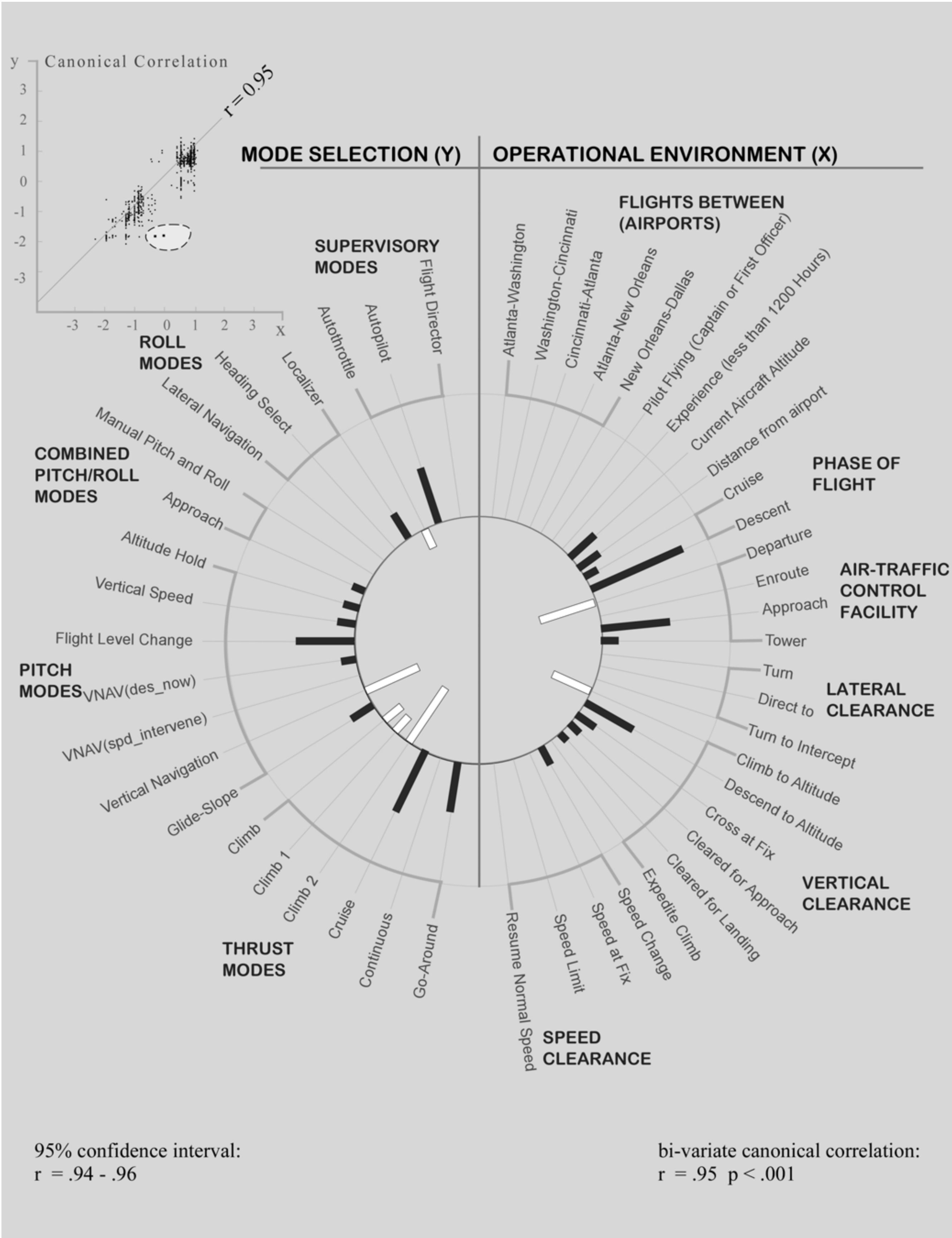

Figure 6. *The first canonical correlation set. The broken line in the bivariate plot of the canonical correlation circles two outliers. These two points indicated a serious deviation from regular operations that was eventually detected by the flightcrews. Had they not intervened, the situation might have transgressed into an incident.*

Note that the patterns not only identify which modes and settings are used ("engaged"), but also which modes and settings are not used. So with respect to the second pattern (white bars), we know that while being controlled by "departure control," pilots hardly ever use the autopilot (i.e., they are hand-flying the aircraft) and are not selecting any lateral guidance from the automatic flight control system. Such information has considerable operational importance for safety and training purposes.

Organization and Packing of Multiple Patterns

The above-mentioned r = 0.95 set is only one of four sets of patterns identified by the canonical correlation analysis. And while it is possible to present each set separately, we decided to combine all sets within a single graph in order to see the overall "story" of how the patterns relate to one another and cover the range of all possible variables. In order to create a composite graph from all eight patterns we decided to use the properties, operators, and processes described in Alexander's theory of centers [1,2,3]. We are finding this theory, which was conceived in the field of architecture, to be extremely helpful and applicable for information organization and presentation.

Alexander's theory describes 15 heuristic properties that help create wholeness in a design and which, for the purpose of our ongoing research, can thereby be extended and applied to the problem of data integration and organization. The first property, *level of scale*, concerns the different ranges of sizes and internal coherence of "centers" within a given design. Thus, after realizing that we have several different levels of statistical strength (significance) among the four sets (0.95, 0.88, 0.81, and 0.72), it became geometrically advantageous to pack them as concentric rings according to their statistical strength. This organization of the sets was inspired by a diagram of the concentric arrangement of houses and storage huts in a typical Trobriand Island village (Papua New Guinea), which corresponds to the social structure in the society [2]. See Figure 7.

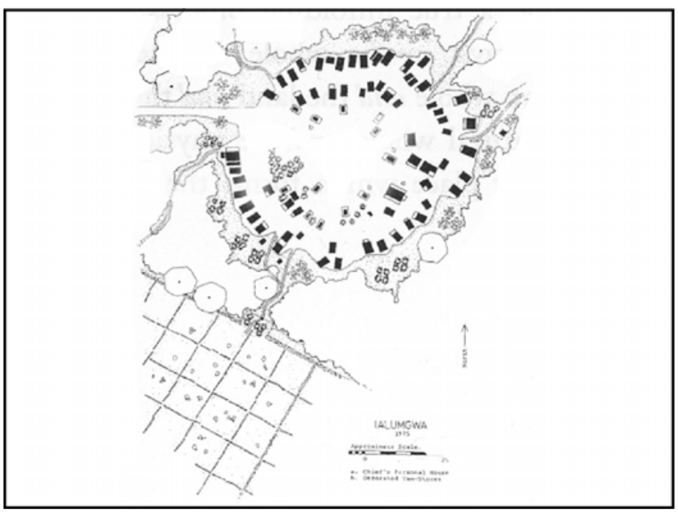

Figure 7. Plan view of a typical Trobriand village. (adopted and reprinted from [2] with permission).

Figure 8 shows how the four sets were organized into concentric rings. (Also note the four respective bivariate plates at the bottom of the Figure). Another property that helps in the organization of geometrical structure is what Alexander calls the *void*—a profound property that is usually placed in the geometrical center of a design to draw the eye inward (e.g., the altar in a church or a prayer niche in a mosque). The rings are organized to (implicitly) suggest that as statistical significance decreases, the shrinking rings collapse into a void.

Elements of Integration

Several properties in Alexander's theory of centers have a strong integration aspect. One of them is *boundary*, which serves to tie a given center with its surrounding space (as a colonnade marks the end of a building and the beginning of the garden, and ties them together). In the Figure, the variable labels form a boundary between the inner world of data (values, significance, etc.) and the outer operational world with its terminology and relationships.

Another property that serves to couple and integrate centers is *interlock*. This property, which is very important for interface design, marks a situation where spaces (or centers) are hooked into their surroundings, causing fusion and coupling. With interlocks the intensity of a given center can be increased by attaching it to a nearby center through a third center that belongs to both. In the Figure, note the cases where there is overlap between black and white bars of the same variable (e.g., "climb to altitude," "Vertical Navigation mode") indicating a strong effect that shows up, independently, in adjacent rings.

Other properties that were utilized in the Figure include *contrast* (between black and white bars) and *gradients* (in the magnitude of bar sizes, which, for the purpose of this display, was abstracted into three categories—strong, weak, and none). *Alternating patterns* and *echoes* are two other properties present in the ray-like spokes that guide the reader's eye as the rings (and variables) become smaller and merge into the void.

Finally, note that in Figure 8 the arrangement of variable labels and their categories (e.g., Roll Modes) is somewhat different than the arrangement in Figure 6. Initially, we arranged the variables names around the ring such that there was an internal structure for the X variables and the Y's. In other words, we viewed them as separate sets. When the composite diagram of Figure 8 emerged, it became very obvious that there is an opportunity to arrange the variables such that pairs of related X and Y variables would be on the same radial (e.g., "clear for landing" and "glide-slope mode"). Naturally, it is also possible to extend this to groups of X and Y variables (e.g., "VERTICAL CLEARANCE" and "PITCH MODES"). This observation was made by both people with expertise in statistics and by subject matter experts. We believe that this insight springs out of the wholeness of the composite diagram (as we have not received any feedback about this issue when we only had separate graphs).

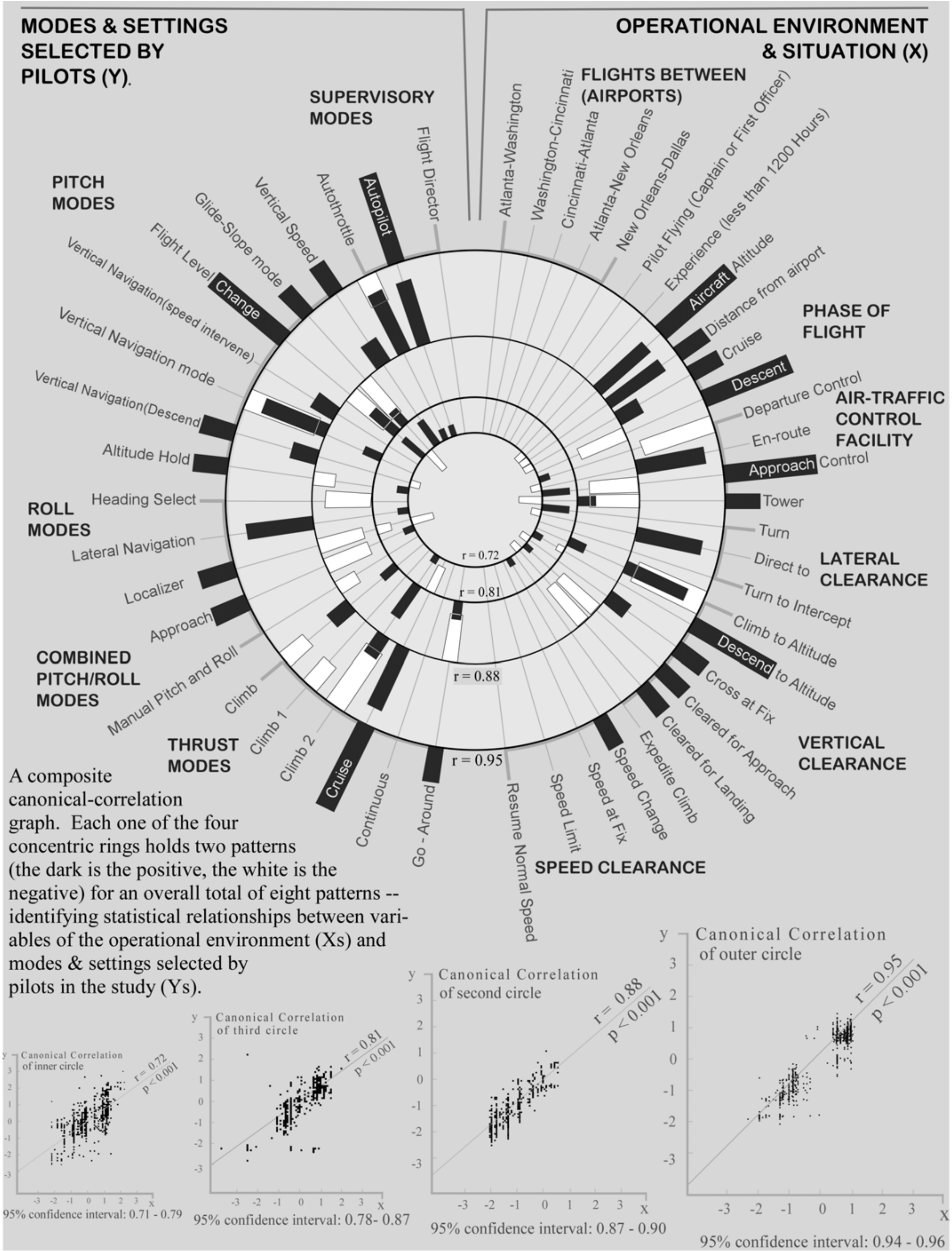

Figure 8. *The final canonical correlation embodying all four pattern sets (r=0.95, 0.88, 0.81, 0.72).*

To conclude, the properties used to create the Figure act together to create a literal sense of wholeness. This allows the reader to inspect the sum total of the patterns in this dataset and identify regions where there is intensity of coverage (where bars of a certain cluster are juxtaposed and where interlocks exist along a certain variable axis), as well as regions on the circumference of the circle that are empty—indicating variables, mostly on the environmental (X) side, that are not important and do not contribute much to pilots' responses. For example, the fact that the "flights between airports" is not important provides a meaningful piece of the puzzle: It assures us that there is nothing of significance about the idiosyncrasies of particular flights. In other words, the patterns are consistent over different flight legs—an important fact about their generality.

SUMMARY AND CONCLUSIONS

In this paper we discussed a conceptual framework for considering the process of representing and presenting information. We then focused our attention on two different abstraction methods: abstraction by rearrangement in the Underground Diagram and abstraction by statistical patterns in human-automation interaction data. Finally, we discussed and applied several aspects of integration and organization.

While the topic of abstraction of statistical data with all its variants (summary, analytical, patterns) is well defined and rests on a sound theory, the topic of information integration and organization, and in particular its application to the problem of packing of large amounts of information, is in its infancy. Concepts of "order," "wholeness," and "coherence" are used in some design communities, yet their definitions depend on the speaker and his or her background. Currently, there does not exist a well-defined theory for information integration and organization, let alone any mathematical foundation for its consistent application. This is a serious shortcoming that is worthy of further research where concepts from art, practical design, and architecture are brought in and extended to the problem of information presentation, and then, perhaps, made into mathematically or heuristically based methods. It may be that our tendency and tradition, in many engineering disciplines, to view and consider information and its theory from a mechanistic and probabilistic aspect [16], have led us astray from the equally important aspect of its semantics, as well as its emotional impact on users [18].

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