A taxonomy of dynamic ATC visualizations

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***Abstract*— Air traffic control systems display information using multiple visual variables. The research described in this paper is an initial effort to develop a theory-driven approach to the characterization of user interfaces. We will focus on the displayed visual object and deliberately leave aside the interaction. In this article, we depict the state of the art in data visualization, and we characterize these systems using the Card, Mackinlay and Bertin model. This work helps characterize images more precisely, refines our understanding of the transformations of the raw data that generates them, as well as the role of perception in the interpretation of visualization.**

***Index Terms*— Information Visualization, taxonomy, graphical coding.**

I. Introduction

Air traffic control aims to maintain the safety for passengers and goods. This task puts them in a complex decision making system. They communicate with pilots using clearances to keep minimal separation of aircraft. The context is highly dynamic; data presented to the air traffic controller come from manifold sources: flight plan, radar data, data link, metrological data, and supervision systems. The decision must be planned in real time and frequently updated. This is the reason why the air traffic controllers' display must be sharp, and must reduce their cognitive workload.

The displays used by the air traffic controllers involve many animated visual entities. They are constrained by precise rules of representation. The richness of these re-presentations highlights the paucity of tools currently available to differentiate them. The increments of such instruments are numerous, in terms of validation, design and safety. The objective of this article is to establish the basis to study representations, to find out methods of characterization that would allow comparisons between representations, and eventually to assess them.

II. Information Visualization

Information visualization (IV) is an expanding field of research, but rare are those who have formalized its non-artistic approach. In the wide range of existing visualization methods, very few of them are actually supported by scientific considerations, and even fewer have been formally evaluated in a rigorous context. Some are starting to address this issue [[25], [28]] and some have summarized it in a framework [[18]].

The Works of Bertin [[1]], act as a reference: "the graphic" is the mono-semantic visual representation of data. We can contrast his formalism with music or modern abstract art, in which the represented data is polysemic (the perceiver can have different interpretations).

The aims of visualization techniques have been fairly well established [[26]]. According to Bertin, the visual data representation has three issues; store data, spread information (the communication is carried out with known data in advance), process information (the handling and the perception of the data allow the analysis and the resolution of the problem). Bertin made simple observations of visual displays. He introduced seven visual variables: position, size, shape, orientation, brightness, color, and granularity. Granularity is often translated as texture, but it really means granularity (as in the granularity of a photograph). Granularity in this sense is also related to the spatial frequency of a texture. Thus, he formulated issues of visual decoding and proposed techniques for enhancing it. But he eschewed principles of vision theory. For psychological theories on Bertin's work, we can consult Kosslyn's books [[13]]. Kosslyn, for instance, introduced the compatibility rules, which leads the semiotic to correspond to the meaning of a graphical representation.

Wilkinson [[28]], among other things, has extended the classification system of Bertin. He prefers the word aesthetics to describe an object in a graphical system, because the word perception is subjective rather than objective, and perception refers to the perceiver rather than the object. Aesthetics turns graphs into graphics so that they are perceivable, but they are not the perceptions themselves.

Mackinlay continued Bertin's work by presenting tools allowing the generation and the validation of graphic interfaces [[15]]. It develops in particular a graphical language to codify a representation.

Tufte illustrated the possible application fields of IV in geographical, historical, economic situations [[26]].

Shneiderman classified visualizations according to the number of dimensions of the displayed data, to the data representation structure (temporal, multi-dimensional, tree, networks). He continued his work by identifying seven minimal tasks to ensure the visualization of the data [[24]] (overview, zoom, filter, details on demand, relate, history, extract).

Card and Mackinlay (C&M) carried out a taxonomy of various charts of information in the form of a table [[5]]. This taxonomy is partially based on the theory of Bertin. C&M applied it to twelve well-known visualizations, such as the ordered matrices [[1],[19]], TreeMap [[11]] or ConeTree [[21]]. This article will detail their work in the following sections.

Tweedy [[25]] doesn't use the noun visualization, she prefers 'externalizations' because it indicates the cognitive role of interactive visual representation. This article introduces one kind of visualization characterization, without the interactions available in visualization. This work focuses on visual representation, therefore interaction will be dealt with in another article.

One of the most important tasks in Data Visualization is to understand the cognitive process involved in the perception of a representation. To reach this goal, the design space must be precisely depicted using taxonomy or a generative procedure. The next section will describe the dataflow formalism.

III. DATA FLOW MODEL

Card, Mackinlay and Shneiderman contribute greatly to our knowledge in the field of visualizations [[6]]. They created a model (Fig. *1*) which describes visualizations as a data processing sequence from the raw data to the display. The processing is based on structures of intermediate data which is easy to handle by the user. Chi detailed the various stages of this model [[7]]. This data flow model is widely used.

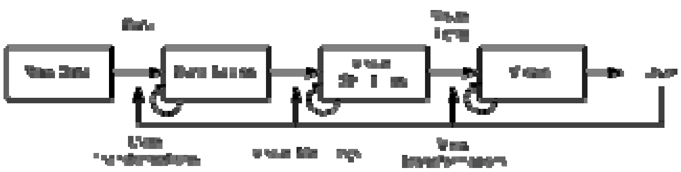

Fig. 1 : Schematic Dataflow of Information Visualization [[5]]

This model is based on the management of a data flow. It is used in many toolkits (InfoViz **[**[10]**],** prefuse, VTK, Tulip, Pajek…) and visualization software (SpotFire **[**[1]**]**, ILOG Discovery **[**[2]**]**, nVizN **[**[28]**]**…).

A. *Data type*

We define the attributes as the typed date from the dataset, and the properties, the visual representation of a data e.g. if we use the color to code the AFL (actual flight level) then the AFL data are the attribute and the color is the (visual) property.

The major distinction we can make for attributes is whether their values are:

- Nominal: are only equal or different to other values (e.g. aircraft call sign),
- Ordered: obey a < rule (e.g. an aircraft's number in the landing sequence),
- Quantitative: can be manipulated by arithmetic (e.g. the aircraft speed).

The quantitative type can be split into two parts: Interval and Ration.

The Interval can derive the gap between values but cannot be null, e.g. the time lapse between 7.00am and 8.00am is the same than 14.00am to 15.00am but we cannot say that 15.00am is twice 7.00am.

The ratio type is the full expressive power of real numbers. The table summarizes the different terms used in the literature.

TABLE 1
DATA TYPES

Bertin [[1]]	**Stevens** [[23]]	**Ware** [[27]]
Nominal	Nominal	Category
Ordinal	Ordinal	Integer
Quantitative	Interval	Real number
	Ratio	

B. *Data structure*

Bertin has suggested that there are two fundamental forms of data: data values and data structures. A similar idea is to divide data into entities and relationships. Entities are the objects we wish to visualize, and relations define the structures and patterns that relate entities to each other.

He defines five data structures: linear, circular, ordered tree, un-ordered tree, and volume. The data structure is the link that clusters the data. In the ATC world, the call sign links the radar data. If we display over time the position of an aircraft, we display a linear data structure.

C. *Data transformation: the metadata*

There is a common misconception about metadata. In a database, metadata are the explanation of a database field (e.g. AFL is the actual Flight level of the aircraft in a dataset). But in IV, Metadata mean data derived from other data, this is a transformation that creates new data out of the existing data.

Tweedy found four types of data transformations (*Fig. 2*):

- Values to Derived Values (e.g. mean processing)
- Structures to Derived Structure (e.g. sorting variables)
- Values to Derived Structures
- Structure to Derived Values

Transformations that switch between value and structure are more complex. Schneiderman, Card and Mackinlay have explained them [[6] p 21-22].

Metadata and raw data are intrinsically different but their representation problems are the same, thus we won't make any special survey for metadata.

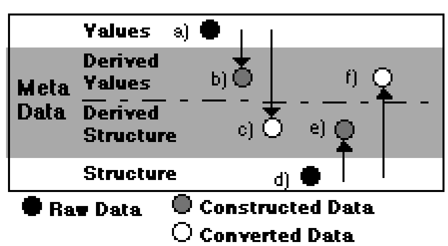

Fig. 2 : Types of Information Represented [[25]]

D. *Data sources*

The data source is the same for manifold ATC visualizations. We are not exhaustive, but mainly, the radar (aircraft position received by the ground radar station), and flight plan (the aircraft path from its take-off to its landing) are the principal data sources. ODS is the main French radar view displayed for the air traffic controllers; Aster is a vertical view of the current flying aircraft, Maestro is an Arrival manager, and ERATO displays future aircraft conflicts.

Fig. 3 : ATC Data source

ATC visualizations display the same information, thus to compare them we need very precise tools.

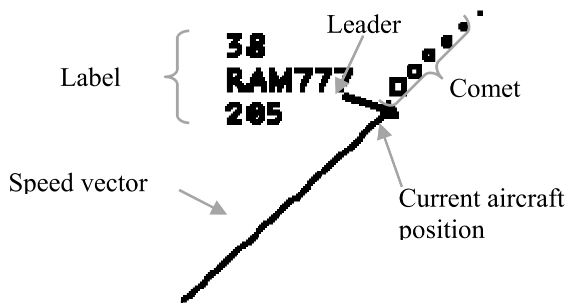

Fig. 4 : the radar track

The *Fig. 4* displays the terms used to depict the radar track.

E. Supervision

Graphics, according to Bertin, have at least three distinct uses (c.f. introduction): store, communicate, discover.

The images of the ATC world are not visualizations dedicated to exploration. They are described as supervision, because the input data change independently of the user. But the user can perform actions on the system; in principle, he tries to improve it. Such action has different levels of criticism: just convenient (giving a direct routing) to critic (avoiding minimum aircraft separation).

The ATC data structure is linked to the attribute named callsign.

F. Implementation

The validation of this transformation model was carried out using software. This software respects the data processing sequences of the data of Fig. 1. It makes it possible to describe the radar image using a dataflow and connections with the visual variables of Bertin (Figure 3).

IV. Metrics and Perceptual Task

Visualization can lead to efficient, accurate visual decoding of encoded information, but may lead to inefficient, inaccurate decoding.

Bertin identified three distinct levels for a visualization analysis: elementary (for a single item), intermediate (for a group of items), and overall (for all the data).

One of the most basic problems humans encounter when using computers is to know what to do to get the computer to solve a particular problem. The second problem is to understand the computered results, what is the graphical meaning of the displayed data. Norman [[16]] identified these two problems and named them the gulf of Execution (how to solve a problem with a computer) and the gulf of Evaluation (what do I see).

The air traffic controller uses supervision interfaces, thus the gulf of execution is reduced. The field of action is limited, and the displayed information fits the interface goal. This chapter will focus on the gulf of evaluations especially on the metrics to compare visual entities.

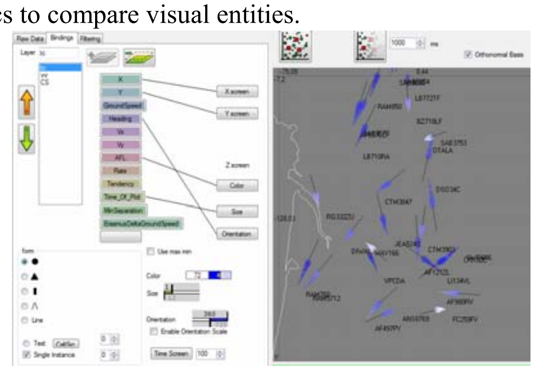

Fig. 5 : dataflow implementation

Cleveland, McGill and then Mackinlay [[15]] built scales of expressivity (monosemic, but dependant on a precise graphical language) and effectiveness (depend on the human perceptual capabilities) to assess alternative designs (*Fig. 6*). This scale depends on the data type. The visual property higher in the chart is perceived more accurately than those lower in the chart. The grey items are not relevant to that type of information. The quantitative data type ranking as been experimentally verified by Cleveland [[9]]. Independently of the data type, the best way to represent the data is to code it with a position on a scale. If we want to represent the speed of an aircraft (quantitative data), we can use the length of a line (speed vector). The aircraft position number in the landing sequence (Ordinal) is better coded using the color saturation than length.

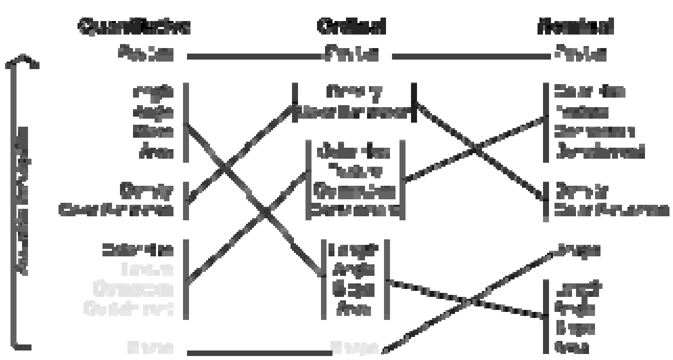

Fig. 6 : Mackinlay ranking of perceptual task [[15]]

This ranking was built for statistical graphs. Air traffic control displays, and other iconic representations of data addressed quite different tasks. But this is a starting point of research.

A. Is Text the most powerful representation?

Despite the fact that the text involves perceptual and cognitive processing that helps one to decode a graphic in the same way that perceiving color or pattern does, the text entity isn't listed in Mackinlay's perception ranking. "Images are better for spatial structures, location, and detail, whereas words are better for representing procedural information, logical conditions, and abstract verbal concepts." Ware [[27] p301-307].

Graphical perception is highly parallel which works on visual properties such as position and color, but has limited accuracy. Text representation is accurate but is limited in capacity. The cognitive workload is very high when we are reading a text.

Paivio used the dual coding theory to explain the difference between text and graphical perception [[17]].

B. Stimulus vs. sensory

The Difference Threshold (or "Just Noticeable Difference") is the minimum amount by which stimulus intensity must be changed in order to produce a noticeable variation in sensory experience. Weber, a medical professor, discovered that the intensity of stimuli may not be linearly related to sensation. The relation between the stimuli and the sensation is formalized in the Weber–Fechner law. Stevens' power law is generally considered to provide a more accurate and general correlation.

Cognitive psychologists have recently turned away from psychophysics toward a more integrated, ecological approach. Because all psychophysical approaches isolate stimuli in order to examine their psychometric functions, the results apply only to certain restricted, indeed artificial, situations. The context is entirely applicable.

Hence, the Kabuki [[2]] project (DTI R&D) aims to propose methods and tools to assess ATC interfaces. The design and the checking of the interfaces allow anticipating the problems of perception and coherence which appear only during the users test, but also, provide the metric to adjust the relative values of parameter settings of the visual objects.

C. Distance and evaluation

Cleveland and Mackinlay rate the position on the scale as the best way to represent a quantitative dimension visually (Fig. 6). This reflects the research finding that points or line lengths placed adjacent to a common axis that enables judgment with the least bias and error. But it depends on how far a point, line, or other graphic is from a reference axis [[14], [22]].

D. Animation

Animation can be done on two levels: with the raw data, and with the visual representation. With the raw data, new data must be created with interpolation. If the animation is based on the visual structures, each entity must have a sole identifier.

Animation helps perception with little cognitive workload. Patterns in moving data points can be perceived easily and rapidly. Given the computing power of modern personal computers, the opportunity exists to make far greater use of animation in visualizing information.

V. Taxonomy

The value of a picture in the communication process is well recognized and one hears the old adage "a picture is worth a thousand words".

Visualization techniques attempt to provoke intuitive appreciation of the salient characteristics of a data set.

It is necessary to use models of characterization which allow the creation of taxonomy and the comparison between the images with a metric. The design space thus described will make it possible to find the non-explored areas and thus of new visualizations. Moreover, this taxonomy will confront the choices of representations, highlight the relevance of the displayed data, optimize the choices of design, and consolidate current knowledge on the relations between representations.

VI. The Card and Mackinlay model

Card and Mackinlay have attempted to establish comparison criteria of the images with their work. They propose a table for each function of transformation (*Table 2*).

Table 2
C&M representation model

				automatic perception						Controles perception	
Name	D	F	D'	X	Y	Z	T	R	-	[]	CP

The lines correspond to the input data. The column D and D' indicate the type of data (Nominal, Ordered, and Quantitative). F is a function or a filter which transforms or creates a subset of D. Columns X, Y, Z, T, R, -, [] are derived from the visual variables of Bertin [[1]]. The image has three and a half dimensions: X, Y, Z plus time T. R corresponds to the retinal perception which clarifies the method employed to represent information visually (color, form, size…). The bonds between the graphic entities are noted with '-', and the concept of encapsulation is symbolized by '[]'. Finally a distinction is made if the representation of the data is treated by our perceptive system in an automatic or controlled way.

TABLE 3
C&M CHARACTERIZATION LEGEND

L	Line
S	Size
f	Function
N, O, Q	Nominal, Ordered, Quantitative
Lon, Lat	Longitude, Latitude
P	Point
O	Orientation

Fig. 7 : ASTER comet

Fig. 8 : Radar comet

A. *ASTER Comet*

The ASTER comet (*Fig. 7*) is coded by a form positioned in (X, Y) on the screen. X screen is the distance between an aircraft and its delivery point at the end of the sector, and Y screen codes the flight level. The size of comet is a function of the ground speed. The vertical speed is coded by the orientation of the comet. Table 4 describes, with the model of C&M, the main graphical transformation of the data set to the ASTER comet.

TABLE 4
ASTER COMET CHARACTERIZATION

Name	D	F	D'	X	Y	Z	T	R	-	[]	CP
Plot	Lat Lon (QxQ)	f	Q	P				Shape			
Afl	Q	f	Q		P						
Vert. speed	Q	f	Q					O			
speed	Q	f	Q					S			

B. *ODS Comet*

The last positions of the aircraft merge by effect of Gestalt continuity [[12]], which makes a line emerge with its particular characteristics (curve, regularity of the texture formed by the points, etc). It is not possible to characterize it directly using the C&M transformation model. But we can characterize individually the shapes which build the comet (*Table 5*). With this intention, we introduce the concept of current time (Tcur: the time when the image is displayed). The size of the square is linearly proportional to its age.

The characterization cannot integrate the result of the analysis by the controllers of the evolution of the last positions of the aircraft (speed, evolution of speed and direction). Thus, in *Fig. 8*, the shape of the comet indicates that the plane turned 90° to the right and accelerated. These data are emergent in the comet. In other words, they were not directly used to generate the image. The characterization of C&M does not make it possible to characterize this essential information for the users, and thus does not allow the comparison of different visualizations objectively. The radar comet is richer than the Aster comet; the characterization of C&M indicates the opposite. The wealth of information transmitted by each representation is thus not directly interpretable in the characterizations: the model of C&M is not adapted.

TABLE 5
C&M RADAR COMET

Name	D	F	D'	X	Y	Z	T	R	-	[]	CP
X	Q Lon	f	Q Lon	P				Shape	emerge		
Y	Q Lat	f	Q Lat		P						
T	Q	f(Tcur)	Q					S			

C. *Comet comparison*

The characterization of the radar speed vector (*Table 6*) shows that its size (Bertin's notation, but as it is a line, we can use the length), changes with the aircraft's speed.

TABLE 6
C&M SPEED VECTOR CHARACTERISATION

Name	D	F	D'	X	Y	Z	T	R	-	[]	CP
speed	Q	f	Q					S			
direction		f						O			

In addition, the same information is coded by the length of ASTER comet and by the speed vector of the radar's comet. The ASTER comet is thus equivalent to the radar's speed vector, modulo a translation. It is the characterization and its comparison which allows it to link two visualizations, and thus to give to the designer elements of analysis. This result shows the importance of the work carried out.

D. *C&M Model conclusion*

The results showed that it is possible to apply such a characterization but it is not sufficiently precise. The radar comet (*Fig. 4*) displays the last positions of the plane (increasingly small squares according to their age) clustered by the Gestalt continuity, which makes a line emerge with its particular characteristics (curve, regularity of the texture formed by the points, etc). It is not possible to characterize it directly using the model of transformation of C&M.

Moreover, it misses the metric for the comparison criteria. The interpretation of the complete characterization of an image is very complex (too many tables). It is thus advisable to extend the C&M model again, or to use a new model.

VII. PROSPECTS

The realization of this taxonomy makes it possible to consolidate current knowledge on the characterization of visualization as our knowledge on the design, perception and the relations between them. The C&M model gives some comparison items but is not accurate enough.

This article captures a state of the art in Information

Visualization. The next part of our job will be to use all those techniques to characterize ATC visualization, and to discover a common framework applicable to every display. A good trial is to find the minimum differences between views. It is easier to describe small modifications than huge changes.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the contributions of Stephane CONVERSY (thesis co-director), Jean-Luc VINOT. A special thanks to all the members of the DTI for their discussions, comments and suggestions.

This work is supported by a PhD scholarship from the DTI R&D and ENAC LII, with the partnership of the IRIT Toulouse, France.

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