A Unified Taxonomic Framework for Information Visualization

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Abstract

We present a taxonomy for Information Visualization (IV) that characterizes it in terms of data, task, skill and context, as well as a number of dimensions that relate to the input and output hardware, the software tools, as well as user interactions and human perceptual abilities. We illustrate the utility of the taxonomy by focusing particularly on the information retrieval task and the importance of taking into account human perceptual capabilities and limitations. Although the relevance of Psychology to IV is often recognised, we have seen relatively little translation of psychological results and theory to practical IV applications.

This paper targets the better development of information visualizations through the introduction of a framework delineating the major factors in interface development. We believe that higher quality visualizations will result from structured developments that take into account these considerations and that the framework will also serve to assist the development of effective evaluation and assessment processes.

Keywords: Information Visualization, Taxonomy, Human Computer Interaction.

1 Introduction

Scientists and Mathematicians have been using data visualization techniques like charts and graphs for hundreds of years. This evidently stems from the fact that man has the innate ability to visually discern order/patterns in what might be considered chaotic data, if not presented appropriately.

The value of pictures in the communication process is well recognized and one often hears the old adage "*a picture is worth a thousand words*". Larkin & Simon (1987) worked to qualify this notion suggesting that information is analogically conveyed through figures and concluded "*a figure is sometimes worth a thousand words*" - depending on what and how information is presented.

The use of pictures and their underlying "*thousand words*" can facilitate a users understanding of the presented information. If visualizations are difficult to interpret, a higher cognitive load is placed upon the user. Au et al. (2000) suggest that interface designers should endeavor to shift the cognitive load from the users' slower thought-intensive processes (e.g. reading words or sentences) to faster perceptual processes (e.g. recognizing patterns and relationships). Sebrechts et al. (1999) support this in their conclusion that a 2D representation allowed for an increased speed and accuracy of analysis of search return assessment compared with text-based tools.

Given the benefits of graphics in communicating complex information it is clear why there is so much interest in visualizing data. The question that we are trying to address is not whether it is worthwhile, but what is the best way to display information for a given application?

This question has led us to focus on the development of a taxonomic framework by surveying current research and forming a framework for IV development. In particular we aim to ensure that the display dimensions are used optimally in terms of maximizing the useful discriminations available to the user in a way that will not result in dimensional overload. Whereas previous attempts to characterize different approaches (Chi, 2000; Tweedie, 1997; Schneiderman, 1996) have tended to focus on just one or two specific factors in interface design, we coalesce proposals of a number of different kinds into a broad framework for the entire field.

1.1 Interface Design Considerations

This paper arose out of research into Visualizations in Information Retrieval (IR) and explorations of the utility of IV techniques in improving the ubiquitous search engine interface or Information Retrieval Visualization (IRV). The use of visualizations as part of the search process has really only started to gain headway in the last few years. Like the field as a whole (Ahlberg et al., 1996), the IRV area has seen very little work in the area of evaluation and taxonomic development. This lack of paradigmatic analysis and characterization of the types of Information Visualization (IV) techniques used is also noted in relation to IV.

This paper begins the process of developing a complete taxonomy for the IV paradigm, by examining the current research in the area and proposing a framework for IV interface development to which further taxonomic definition can be associated. Although our motivation, applications and examples come from IRV, the taxonomy aims to be applicable to IV in general.

1.2 The Human Problem

When humans present themselves to a computer with the aim of using it in some targeted and meaningful fashion they are faced with what is in some ways a very non-intuitive device. This is one of the two most basic problems humans encounter when using computers; the problem of knowing what to do to get the computer to solve a particular problem. The second difficulty is that of knowing how to interpret the computers presentation of the material. Norman (1997) recognizes these two problems and describes them as the two gulfs a user must ford in using any computer artifact (see Figure 1):

1. The **Gulf of Execution** (how do I state/present my question?).
2. The **Gulf of Evaluation** (how do I interpret what has been presented to me?).

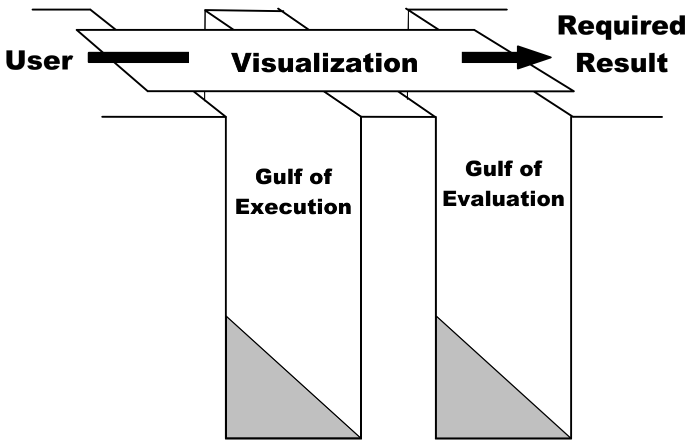


Figure 1. Gulfs of Execution and Evaluation

Card et al. (1991) highlight the Gulf of Execution problem, stating: "*it is difficult for users to ask an information retrieval system for what he or she wants, because the user does not, in generally, know what is available and does not know from what it has to be differentiated*".

These two gulfs are the starting points for any definition of an IV taxonomic framework, both in an IR context and more generally. They flag the fundamental issues that designers must overcome in relation to the nature of the user and their objective. The purpose in moving to a visualization interface for the task relates to moving out of this difficult question/answer mode into a more flexible exploration mode.

The process of getting the user from the point of sitting down in front of the IV system to achieving a result is thus not a single linear process from action to result. The user will go through several distinct phases, some of which may be repeated, due to the process of refinement and exploration. Mann (1999) discusses this very issue suggesting there are four distinct phases within the process of constructively using visualization: *formulation, initiation of action, review of results, refinement*. These dimensions fit well into the overall IV field. We generalize and adapt them as follows:

- *Formulation* sees the user deciding if, what and how they will use an IV to achieve a certain result.
- *Initiation* is the starting of a process by the user requiring some form of input/interaction with the interface.
- *Review of results* sees the user interpreting what has been presented to them and deciding if there is a need to change the way in which they started or if they need to refocus or adjust the viewpoint.
- *Refinement* occurs if, during the review process, the user decides that they need to either restart the process with a different tack or, refine the process. This stage requires the user to start over with the (re)formulation stage, applying what they have learnt from the previous round in the process.

Since each distinct stage present different requirements with regards to communicating information we use them as the part of our framework (see Figure 2).

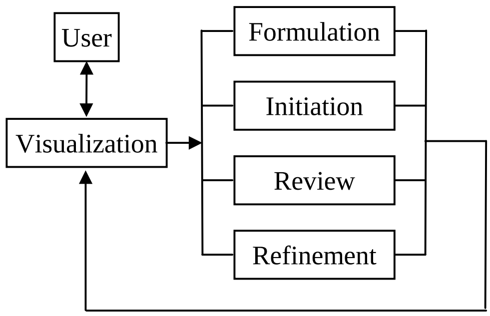


Figure 2. User Interaction Phases

2 Interface Design Factors

When considering the design aspects of an IV interface five factors should be considered in relation to the target application and the intended users;

- *Data*
- *Task*
- *Interactivity*
- *Skill level*
- *Context*

2.1 The Data Factor

When using any form of IV the user employs the benefits of data abstraction, implying a connection between the user and the computer. This connection can be seen in the data as it is the common ground between the two. It is this commonality that spurs Benyon's (1992) data-centric approach, which stems from his notion that "*data is probably the only thing people have in common with computers*". It also underlies Chi's (2000) data state reference model and taxonomy.

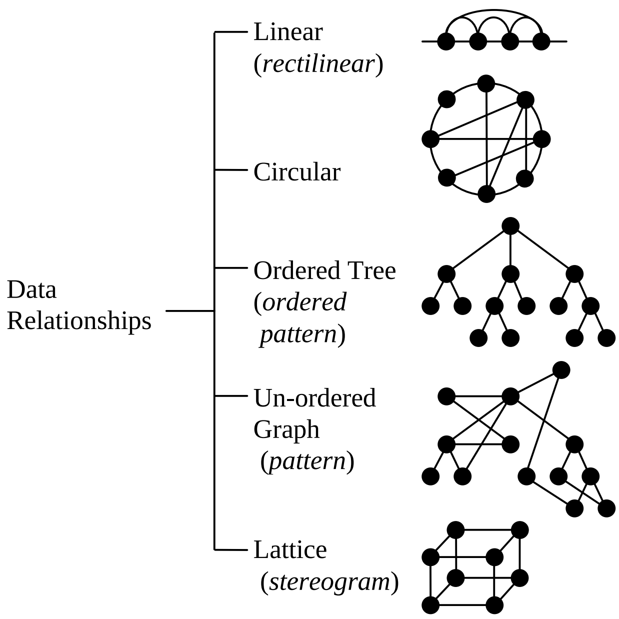
2.1.1 Data Types

Bertin (1981) suggests that when interacting with data there are three different levels on which you can interact on, these being: *a single item, a set of items, or the whole set*. Tweedie (1997) extends this in suggesting that there are two different types of data interactions. These are interactions at the *attribute* level of the data or the *object* level of the data. Given there are three possible levels and two different types of interactions it can be seen that this actually results in six different types of interaction. These types only account for *low-level* data which suggest a third dimension of interaction, that of the interaction with *meta-data*.

2.1.2 Data Relationships

Mattis and Roth (1999) give further definition to the concept of data in proposing several dimensions along which information can be characterized to support visualization, the key dimensions being the **Data Type** and the **Relational Structure**. They also suggest that "*Other dimensions reflect the user's immediate information-seeking goals…*" and that they may also reflect "*…the relatedness of different information subsets*". In these we see our other suggested factors, namely: the *Task* itself and the *Context* of use.

The **Relational Structure** mentioned above describes the way in which data is structured. Bertin (1981) identifies five types of relational structure Linear (*rectilinear*), Circular, Ordered Tree (*ordered pattern*), Un-ordered graph (*pattern*) and Lattice (*stereogram*). These structures describe the way in which data is positioned within a data collection and are described in Figure 3.



Adapted from; Bertin, J., (1981)

Figure 3.Data Relationships

At this point we meld what has been proposed into one Figure to represent the underlying information (see Figure 4). This indicates that any underlying data can be defined by two general definitions: data type and data-relationship.

Data Type can be divided into two types of data: high-level and low-level. Low-level data being described as being either *objects* or *attributes*. High-level data is described as being meta-information.

Data Relationship is broken into six different categories describing the way in which data collections are structured. They can be *linear*, *circular*, *ordered tree*, *unordered tree* or *hyperspace*.

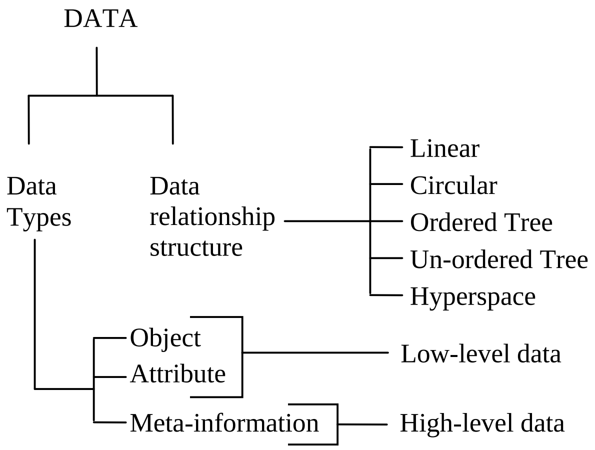


Figure 4. Data Dimensions

2.2 Task Factor

Task we define as being what the users aims to achieve and how they achieve it using all or part of an interface's functionality.

With a broad scope, Schneiderman (1998) deconstructs the "Task Factor" appropriately in his "Data Type by Task Taxonomy". He divides the *task domain* into seven distinct dimensions each of which represent "*…task-domain information actions that the users wish to perform*". As described in Figure 5, these dimensions are:

- **Overview**: a view of the total collection.
- **Zoom**: a view of an individual item. This may be either at the *object* or *attribute l*evel.
- **Filter**: removing unwanted items from the displayed set.
- **Detail-on-demand**: getting the details of a selected group, sub-group or item.
- **Relate**: viewing the relationships between a selected group, sub-group or item.
- **History**: the actions of undoing, replaying, and refining using a store of historic information.
- **Extract**; the extraction or focusing in on sub-collection and other parameters from a given set.

The actions a user carries will be peformed within the context of broad task such as Data Mining, Database Query, Data Analysis, Information Retrieval, etc., and this becomes a specific context for the interface design.

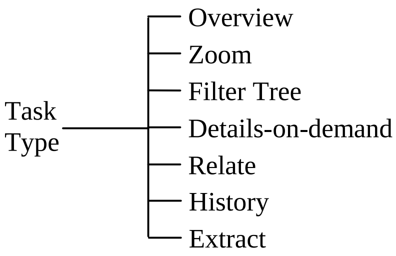


Figure 5. Task Dimensions

Directly affecting the way a user interacts with the visualization are the specifics of the data and the task as well as the level of user skill. We now turn to discuss this interaction between task and skill factors in some detail.

2.3 Interactivity Factor

The problem presented by the "Gulf of Execution" is further exacerbated when dynamic user interaction is involved since it requires the development of systems to give feedback to the user. These systems help the user understand and manage transformational events and context such as; where they are with regards to their last action, and the data structure and how they got there.

Mukherjea et al. (1995) suggest that interaction with a graphics interface involving structural transformation can markedly improve a user's contextual understanding. In other words, if the interactions are appropriate, the user develops contextual understanding about the data while acquiring experience about how the interface works. From this the user can gain the two benefits:

- Users can begin to predict what types of actions might produce the required result. This basically allows the user to decide what tool might reduce their workload both cognitively and physically.
- In working contextually with the data, users develop their own mental map with regards to their contextual relationship with the data displayed. This can be seen as addressing the problem of the Gulf of Evaluation.

In highlighting the importance of the users' interaction we see that a defining structure is needed to generally describe the field. Tweedie (1997) addresses this when suggesting that any interaction with an interface can be seen as falling along a continuum between using tools that allow direct manipulation and using tools that fully automate a transition process. Figure 6 describes this continuum as being terminated by fully DIY at one end and fully automated at the other.

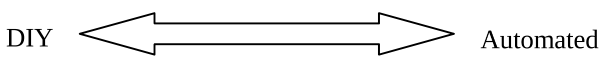
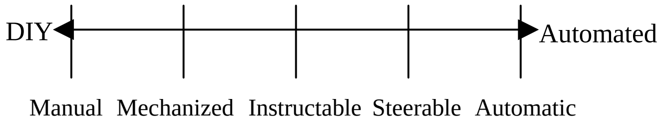


Figure 6. Interactivity Continuum

This continuum can be further broken into the landmark interaction types illustrated in Figure 7:

- **Manual** (e.g. dragging something with a mouse)
- **Mechanized** (e.g. using a tool to make focused selections as seen in pull-down menus)
- **Instructable** (e.g. formulas in a spreadsheet)
- **Steerable** (e.g. using an algorithm that can be instructed to perform in a certain way)
- **Automatic** (e.g. allowing a program to perform undirected to achieve a result)

Figure 7. Segmented Interactivity Continuum



The manner in which information is presented to the user greatly influences the quality of any such manipulation. For the user to know which modes to work with, they need an appropriate abstraction presented to them both prior to the original interactions and subsequent interaction. Thus, feedback in the form of transition effects and results presentation are critical to the user being able to track and assess the result of their interaction. In this way the rules governing the interaction are externalised allowing users to observe and thus have the chance to learn from the result of their actions.

Norman and Drapers (1986) identify four classes of relationships in this regard:

input $\rightarrow$ input (two handed input)
input $\rightarrow$ output (operation of a slider)
output $\rightarrow$ input (error messages)
output $\rightarrow$ output (link two output displays)

There are also time implications being communicated by the relationships. For example users often need to compare past and current query results in deciding their subsequent actions. This helps the user assess the quality of the result and possibly in predicting the potential state after a given input. This also assists with the "lost in *n* dimensional space" problem by helping with navigation through historic information feedback and assessment (e.g. have I searched or been in this area yet?).

Different presentation techniques suit different data types and as such we suggest that the data type directly influences the type interactivity required and have combined information type and interactivity type to form a matrix (see Figure 8) to classify interfaces. There is also dependence between the interaction capabilities and the dynamism and animation of the visualization, both of which we discuss in section 4.

High-level information	Meta Info	Bead, Enhanced Scatterplot Spreadsheet, …	Hypergami, Influence Explorer, Pad++, …
Low-level information	Data	Scatterplot Matrix, Table Lens, Cone Tree, …	InfoCrystal, Attribute Explorer, …
		Direct	Indirect
		Interactivity type	

Adapted from: Tweedie, L., (1997)

Figure 8. Data & Interaction Matrix

2.4 Skill Factor

It stands to reason that the skill level of the user will affect the quality of any outcome. Novices are obviously not going to have as much success as those that are seasoned or professional users of the IV. This is demonstrated in a series of evaluations conducted by Sebrechts et al. (1999). Their results from analyzing the comparative value of Text, 2D and 3D, using different incarnations of NIRVE, demonstrate that success for a given user task improves as experience increases. There is a considerable decrease in time to complete a task in using 3D, a moderate decrease for 2D and a marginal increase for Text across 6 sessions. On average, successive tasks of the study were more complicated but times to complete tend to improve for subsequent tasks notwithstanding the increasing difficulty,.

This provides another dimension to use when defining an IV, that of skill level. This is demonstrated in Figure 9 as a continuum between Novice and Expert. Because a users skill level requires different presentation and interaction techniques to elicit appropriate user interaction, this dimension will need different approaches for the output and interaction factors.

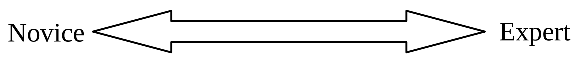


Figure 9 User Skill Continuum

2.5 Context Factor

Context, in respect to this framework, describes those factors that are external to the use of the computer artefact, but influence the user in the use of the IV. There is little research in this area of IV. However, Ahlberg et al., (1996) allude to the need to look in this direction from perspectives such as share-usage and unshared usage (e.g. by a single user with a single intent or group of users with a common focus, either as short term one off event or over a period of time).

With regards to a framework we propose six contextual dimensions (see Figure 10) the IV designer should consider, these being the users:

- **Life Experience**: accounts for such things as computer skills, previous experience in a field, etc.
- **Intent**: describes what the user thinks they want from using the IV.
- **Need**: describes what the user actually needs from the use of the visualization. This may evolve through the use of the IV.
- **History**: describe the IVs usage by the user - is it a one-off use (e.g. looking up the meaning of a word) or does it pertain to an ongoing activity (such as research in a field over many months or years)?
- **Device**: the type of device used to display the visualization (e.g. projector, PC, laptop, handheld computer, etc) will affect the way in which the user can or might prefer to interact.

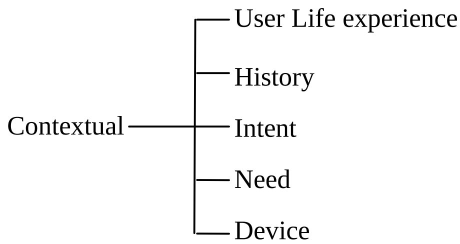


Figure 10. Contextual Dimensions

3 Input

Any IV will be the result of some user interaction. This raises the question of what are the relevant factors with regards to input?

Whether refining a process or starting from scratch, two factors will impact the input process: the *Tool* and the *Device*.

3.1 Tools

An IV Tool is any soft device used to interact with the visualization. The previous discussion on Interactivity (see section 2.3) implies that different software tools or widgets will be used to achieve different types of outcome depending on the interactivity type. However, at the root of all tool use will be some form of direct interaction. This can be seen in the user needing to point, click, drag, etc, something somewhere on the screen to achieve an end result notwithstanding any secondary action. By *tools* we are specifically referring to soft tools used to interact directly with the display. These may or may not result in further secondary indirect processing. Thus, by the term *tools* we are referring to the software mechanisms that allow interaction with the display rather than hardware input devices themselves.

3.2 Device Design Taxonomies

As a key part of the interface, input devices are critical to the visualization, however, it bears only small relevance to this taxonomic development, and as such will only be treated briefly.

In their development of a single framework for input device development Card et al. (1990) identify three-development areas: toolkits, taxonomies and performance studies.

With respect to taxonomy, two approaches have been forwarded to help systematize the design space of input devices:

- Foley et al. (1990) focus on computer graphic subtasks by classifying each device under the subtask it performs (e.g. palm pilot pen and tablet is capable of character recognition).
- Baecker and Buxton (1987) classify input devices by the number of spatial dimensions they sense and their physical properties.

4 Visualization Approaches

We consider two general ways information can be presented to a user – as text or as some form of abstracted pictorial representation – and ignore for the present other possibilities (e.g. speech). Current IVs tend to be hybrids, combining both text and graphics.

The key problem with text representation is that despite allowing a high level of definition it requires a large amount of cognitive effort and does not draw on the users inherent ability for pattern spotting and analysis. Pictorial representation is espoused because it allows the user to lower their cognitive load and draw on their pattern spotting and visual analysis abilities, not just because the visualizations are pretty – although for some IVs the aesthetic value may be the only advantage of the visualization.

These approaches do not have to be distinct with regard to IV approaches. A meld of the two is often a very powerful tool especially when tailored to different task outcome requirements. This is shown in the multivariate approaches taken by Card et al. (1996) and Robertson and Mackinlay (1993).

Once again we see a continuum formed between dimensions as illustrated in Figure 11 with Text terminating one end of the continuum and Pictographic the other.

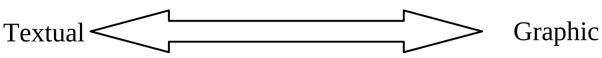


Figure 11. Presentation Form Continuum

4.1 Display Dimensions

It is clear that to describe the display or presentation paradigm for IV one must look at the dimensions the device can depict. Any screen displaying information only has eight dimensions through which the IV designer can work to convey meaning: *plane, colour, value, size, texture, orientation, shape* and *relationship*.

- **Plane**: the coordinates that identify the position of a displayed component – e.g. Cartesian x,y pixel coordinates.
- **Colour**: any colour in the visible range with varying RGB or CYM.
- **Value**: is any component indicator that that conveys a value difference between it and other components.
- **Size**: the percentage of screen area the component uses.
- **Texture**: surface patterning used to differentiate components and communicate extra meaning.
- **Orientation**: a components angular positioning with regards to the bounds of the display or other components.
- **Shape**: the shape a visual component takes on the screen
- **Relationship**: a component's position (Δx, Δy in Cartesian terms) relative to another component.

These dimensions can be further sub-classified by applying Bertin's (1981) image variable dimensions. These can be seen as gathering *plane, size, value* and *relationship* under the "Variables of the Image" dimension and *texture, colour, orientation* and *shape* under the "Differential Variable" dimension. Figure 12 illustrates these display dimensions.

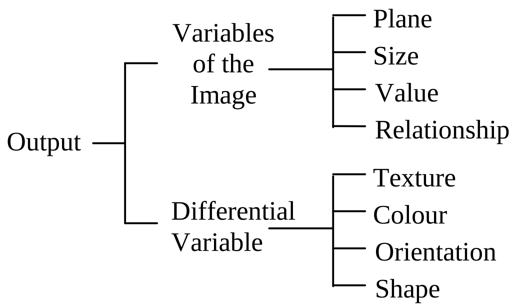


Figure 12. Output Dimensions

4.2 Display Dynamics

Display dimensions can be further refined in terms of the type of display usage. If output is presented to the user in such a way as to not allow interaction it can be described as *static*. Alternatively, if interaction is allowed it will be described as *dynamic*.

Depending on the type of interaction IV designers will need to modify their visualization to account for the usage type. Static displays need to present information in such a way as to allow the user to see and extrapolate any needed information from that one representation of the result. Dynamic displays need to present information in such a way that allows the user to predict what type of interaction they will need to perform next (e.g. what process needs to come next given the visual result of the last process?). Dynamic displays can present information in a static style (e.g. the result represents some final state that does not need further refining/mining), but in general admit the possibility of modification. Figure 13 describes this approach as an initiating process that may or may not result in further processing depending on the display approach.

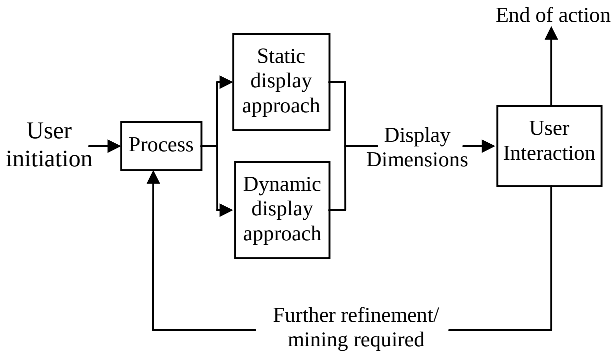


Figure 13. Static and Dynamic Display Interaction

4.3 Display Animation

The concept of dynamic interaction is closely related to that of motion and change, since interacting with the view will result in a change in the view. However, motion and change constitute an entirely independent dimension, and are integral to the animation approaches to visualization. This is a major aspect of visualization in its own right and we will not address it directly here, although, we do wish to touch on some of the psychological implications of motion and animation.

The human visual system is extremely sensitive to motion and something that may not be detected in a static visualization or if there is too much latency in transitioning between successive views, would be perceived instantly if it moved dynamically relative to a static background. This is a well-known property of visual systems, is a particularly salient attribute of our peripheral vision capability, and also seems to lie behind our instinct to freeze in the face of danger. Animation may also be fruitfully employed to highlight information that is particularly important for the user to perceive quickly.

Animation is most commonly conceived of as relating to objects moving, but changes in apparent size, brightness or colour, are similarly salient and all such dynamic variations may be regarded as aspects of animation.

5 Dimensional Overload

The usefulness of an IV depends on the number of concepts, or “data facts”, the user needs to assess at any one time. We define a data fact as a data attribute or a data object where a data object is defined recursively as a single atomic object or a grouping of data objects (cluster). Fairly obviously the more data facts presented the more confusing the visualization can become.

We regard the cognitive load a visualization places on the user as a major dimension that has not been adequately explored in visualization research. For the field to advance it is appropriate to borrow psychological methodology and theory to explore the question of how much information we can usefully convey with a visualization, and this needs to be an integral part of our characterization and assessment of a visualization.

5.1 Implications for Visualization

Although our exploration of this aspect of our taxonomy is at an early stage, and beyond the scope of this paper, it leads us to propose that there are several things a developer should keep in mind when dealing with the output dimensions. We give the following as examples of the kind of factors we need to consider, based on some basic perceptual limitations (Miller, 1967):

- Attribute Resolution: For representation involving a single output dimension only six or seven distinctions can be handled without conscious processing.
- Number of Attributes: It seems that it is pointless to visualize more than six or seven display attributes to distinguish data facts, and even then the attribute resolution that can be subconsciously processed and recalled may be limited to only two or three distinctions in each dimension.
- Explicit and Implicit Grouping: It is useful to represent data facts in such a way as to allow the user to subconsciously group and recode, and whilst clustering techniques explicitly recode to help to limit the amount of detail, visualizations showing natural clusters convey the same information implicitly but at multiple levels simultaneously.
- Views and Cues: When providing new views it is important to have cues that help the user “clear out” the old information in the dimensions that users are going to reuse. In addition it is useful to provide cues to help users discern the relationships and continuity between views. Various animation techniques can serve one or both of these purposes.
- Sequential and Parallel Presentation: Distinctions that may not be salient in a simultaneous presentation may become salient when the presentation is animated, so that time becomes an additional dimension available to contrast data objects or present or reinforce a specific attribute.

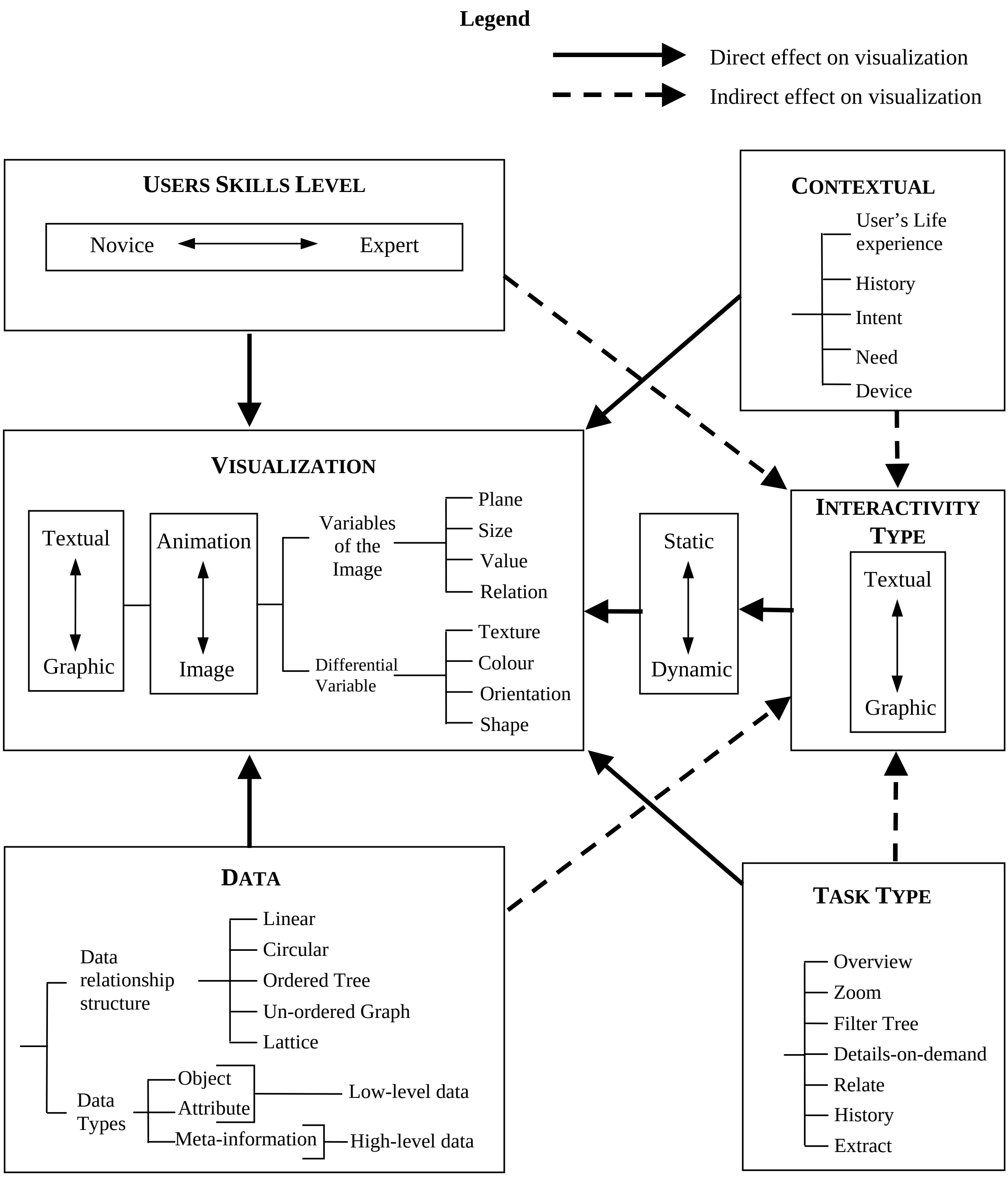


Figure 14. Taxonomic Framework

6 Conclusion

The usefulness of interactive mechanisms is widely identified despite little constructive taxonomic development in the area. Simon (1997) identifies this need for taxonomic development as far back as 1969. However, tools with expanded capacity are taking users beyond their everyday understanding of physical object (e.g. allowing them to operate on *n* dimensional space or even perceive multidimensional relationships in a 2D environment). Unintuitive developments like this may actually be counterproductive and negate the benefits that might be derived from visualization.

This leads us to this papers target of the better development of information visualizations through the supply of a framework detailing all major areas of development consideration. In doing this higher quality visualizations should result from structured developments that sees all critical considerations made and being supported by comprehensive assessment processes. Whilst Chi's (2000) taxonomy is not actually a taxonomy for visualizations and focuses on categorizing the processing steps leading into a visualization rather than the visualization techniques themselves, it is useful in describing visualization systems in terms of his Data State Model, thereby allowing for reuse of data transformations between various systems.

Our framework addresses all the major factors involved in getting the user successfully from problem to solution across the gulfs of execution and evaluation. These factors being the:

- Data type and data relationships.
- Task type.
- Interactivity type.
- User skill
- Context of the IVs use.

These factors are combined with the output dimensions in Figure 14 to form a graphic representation of a framework that can be used for taxonomic, development and assessment purposes.

We have also incorporated a number of factors relating cognitive load to the allocation of output dimensions. We believe these kinds of consideration will be useful in guiding the developer towards visualizations that are amenable to our powerful subconscious visual processing capabilities rather than requiring conscious sequential logical processing. This is an area that is important to explore both from a theoretical and an empirical perspective.

We are currently developing interfaces and evaluation techniques to explore the utility of this taxonomy and explore our specific output dimension and cognitive load heuristics. At the same time, we are finding the taxonomy and the identified design factors provide significant insight and guidance in the design and evaluation of new information retrieval visualizations and interfaces.

7 References

Ahlberg, C., Korfhage, R., Plaisant, C., Chalmers, M., Rao, R., and Hascoët-Zizi, M. (1996): "Where is information visualization technology going?" Proceedings of the 9th annual ACM symposium on User interface software and technology, November 1996.

Au, P., Carey, M., Sewraz, S., Guo, Y., and Rüger, S. M., (2000): "New Paradigms in Information Visualization". Proc of the 23rd International ACM SIGIR Conference (Athens, Greece, 24-28 July).

Baecker, R. and Buxton, W., (Eds.), (1987): "Readings on human-computer interactions: A multidisciplinary Approach", Los Altos, CA: Morgan Kaufmann, pp357-365.

Benyon, D., (1997): "Task analysis and system design: the discipline of data", Interacting With Computer, 4 (1), pp.246-249, 1992, (referenced in [Tweedie 1997])

Bertin, J, (1981) "*Graphics and graphic information-processing*", Berlin ; New York : de Gruyter.

Card, S., Robertson, G., and Mackinlay, J., (1991): "The Information Visualizer, an Information Workspace", Proceedings of ACM Human Factors in Computing Systems Conference (CHI `91), pp. 181-188.

Card, S., Robertson, G., and Mackinlay, J., (1990): "The design space of input devices", Conference proceedings on Empowering people: Human factors in computing system: special issue of the SIGCHI Bulletin: Human factors in computing system: special issue of the SIGCHI Bulletin, March, 1990.

Card, S., Robertson, G., and York, W., (1996): "The WebBook and the Web Forager: An Information Workspace for the World-Wide Web.", In Human Factors in Computing Systems: Proceedings of the CHI ' 96 Conference. New York: ACM, 1996. http://citeseer.nj.nec.com/card96webbook.htm

Chi, E., (2000) A Taxonomy of Visualization Techniques Using the Data State Reference Model, In Proceedings of InfoVis 2000 (Salt Lake City UT, October 2000), IEEE Computer Society, 69-75 http://citeseer.nj.nec.com/chi00taxonomy.html

Foley, J., Wallace, V. & Chan, P., (1984): "The human factors of computer graphics interaction techniques". IEEE ComputerGraphics & Applications, 4(11), pp.13-48.

Larkin, J. H., and Simon, H. A. (1987): "Why a figure is (sometimes) worth a thousand words", Cognitive Science, 11:65-99, Reprinted in "*Figurematic Reasoning: Cognitive and Computational Perspective*", Glasgow, J., Harayanan, N. H., and Chandrasckaran, B. (eds.), AAAI Press / The MIT Press, 1995, pp.69-109.

Mann, T.M, (1999): "Visualization of WWW-Search Results", Proceedings of the International Workshop on Web-Based Information Visualization (WebVis' 99), pp. 264-268, http://citeseer.nj.nec.com/mann99visualization.html

Miller, G. A., (1967): "The magical number seven, plus or minus two: some limits on our capacity for processing information". In The Psychology of Communication, pp.14-44, reprinted *Psychol. Rev.* 63:81—97.

Mukherjea, S., Foley, J., and Hudson, S., (1995): "Visualizing Complex Hypermedia Networks through Multiple Hierarchical Views". Proceedings of ACM SIGCHI '95, May. http://citeseer.nj.nec.com/mukherjea95visualizing.htm

Norman, D., (1997): "The Psycholgy of Everyday Things", 1988, Basic Books, referenced in Lisa Tweedie, Characterizing Interactive Externalisations, Proceedings on Human factors in computing systems, March.

Norman D., and Draper S. (1986): "User-centred system design", Lawrence Erlbaum (ed.), in Norman, D. and Draper, S., "*User Centred System Design*". LEA, Hillsdale, NJ (1986).

Robertson, G., and Mackinlay, J., (1993): "The document lens", In Sixth Annual ACM Symposium on User Interface Software and Technology, December 1993.

Roth, S. and Mattis, J. (1990): "Data Characterization for Intelligent Graphics Presentation", in Proceedings of the CHI'90 Conference (Seattle, April 1990), ACM Press, pp. 193-200. http://citeseer.nj.nec.com/roth90data.html.

Sebrechts, M., Cugini, J., Laskowskii, S., Vasilakis, J., and Miller, M., (1999): "Visualization of Search Results: A Comparative Evaluation of Text, 2D, and 3D Interfaces", in "Research and Development in Information Retrieval", pp.3-10, accessed at: citeseer.nj.nec.com/sebrechts99 visualization.html, access on 12th Aug 2002.

Schneiderman, B., (1998) "Designing the User Interface. Strategies for Effective Human-Computer Interaction", Addison-Wesley, Reading, Massachusetts, pp.523-524.

Simon, H. A., (1969) "The Science of the Artificial", MIT Press 1969 (referenced in [Tweedie 1997]).

Tweedie, L., (1995): "Describing interactive visualization artifacts - DIVA", in the Conference on Human Factors in Computing Systems, May 1995, p.73-74.

Tweedie, L., (1997): "Characterizing Interactive Externalisations", In Conference on Human Factors in Computing Systems, March 1997, pp. 375-382.