12th ICCRTS

"Adapting C2 to the 21st Century"

Title: Scientific and graphic design foundations for C2

Topics: C2 Concepts, Theory and Policy, Cognitive and Social Issues, C2 Metrics and Assessment

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Scientific and graphic design foundations for C2

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Abstract

Whether designing from scratch or modifying an existing command and control (C2) platform one should always take into account the vast amount of background research that has been performed in both the psychological as well as the graphical design literature. However, surveying this vast literature can be daunting as well as overwhelming if one's background is not in the applied science (e.g., psychology). A review is given of the most relevant issues in the literature as well as how the findings may be applied. For example, for graphical design the work of authors such as Tufte, Ware, and Healy is discussed, and how their approaches help one to better design graphical interfaces. Likewise, a review of the psychological literature will discusses issues such as attentional capacity issues (e.g., attentional capture, change blindness) and memory issues (short versus long term versus working memory), among others. Finally, a proposed method for taking into account and applying these principal for the design of an optimal C2 system is discussed.

Introduction

Modern C2 operations are becoming increasingly complex. At the same time, the deluge of information generated by the increasing use of advanced sensors and networks in the battlefield exerts tremendous informational and perceptual load on commanders. The massive amount of data that flows from different sources makes it difficult for users to understand the information available. Commanders may also have difficulty in extracting required information from the constant streams of data resulting in critical data sources being ignored or not well utilized, because the visualization techniques for presenting information on current C2 systems are limited. The difficulty in understanding and exploiting all available information may lead to a reduction in the effectiveness in the conduct of military operations.

C2 developers need to have a deep understanding of how humans perceive and process information visually, make sense of information, and interact with computer interfaces, so as to increase the perceptual, cognitive, and information utility of C2 systems. They should take into account the vast amount of background research and development that has been conducted in graphic design, perception, and cognition literature.

This paper reviews the most relevant concepts in the literature on graphics design, visual perception, cognition and information visualization evaluation that exploit human innate capabilities to enable rapid perception and understanding in the design and development of C2 systems. The paper is organized as follows: the first section outlines the graphic design guidelines that exploit pictographic and typographic elements to enhance visual communication of information; the second section describes empirically tested principles and theories on how humans perceive and organize visual information that can be applied to the design and development of C2 related information visualization; the third section relates issues of human memory to C2 displays; the fourth section discusses evaluation guidelines and takes a task-oriented approach to describe the evaluation of information visualization systems; finally the last section concludes by describing a proposed method for taking into account and applying these principles for the design of C2 system.

Graphic Design

Users gain insight from visualizing the dataset when the intended message of the dataset is communicated effectively to the users. The communicative value of the visualization can be enhanced by graphic design which uses pictographic and typographic elements to create effective visual communication. Graphic design can help to emphasize the important features and relationships in the dataset while minimizing the distracting effects of extraneous details and also improve the presentation of the task information through careful selection and arrangement of graphical elements to establish clear visual relationships among the elements in the composition. This section presents a summary of the concepts in graphic design layout, typography, color, and data graphics that would serve as the basis in designing the visualization.

Layout

Layout concerns how the graphical elements are placed in the composition to achieve fast and accurate comprehension. The primary considerations of layout are proportion, format, and grid system. The classical proportions used in graphic design provide aesthetic appeal and can be used to define the boundary of the graphical elements as well as the overall composition. They consist of the square, square root of 2, golden rectangle, and double square (Marcus 1992). The format refers to the outer boundary of the composition. The grid divides the format into sets of horizontal and vertical lines for placement of graphical elements. The grid system is used to define key alignments of graphical elements within the composition as well as to establish a visual hierarchy of the graphical elements to facilitate the scanning of information. Decisions on the placement of graphical elements can be complemented by the use of Gestalt principles (see Section 3.3) to assist the users in perceiving and recognizing patterns in information.

Typography

Typography is the art and technique of designing textual information using a combination of typeface, type size, line length, line spacing and letter spacing. The goal is to optimise legibility and readability of the textual context to facilitate interpretation and comprehension of the information. Typeface refers to the name of the type such as Times new Roman or Arial and is broadly classified as either serif or sans serif. San serif typefaces are generally recommended for screen of low resolution or the type is 10 points or smaller (Galitz 2002). The details of the serif typeface are lost when the type is small in size. Due to the low resolution of the screen, type sizes of 12 and 14 are recommended to provide comfortable reading although 10-point type is legible in small amounts (Kahn and Lenk 1998). The number of typefaces used in the visualization should be limited to three in a maximum of three sizes (Marcus 1995) as too many typefaces may distract the users from reading the information.

For continuous reading tasks, mixed case text is recommended. The use of upper case text can slow reading speed by 12 percent (Marcus 1995). For non-reading tasks such as identifying single word or short phrases, performance is better with upper case text (Tinker 1963). Upper case text could be used for screen headings or cueing important items such as warning (Galitz 2002). A range of 40-60 characters per line is a comfortable maximum for reading (Marcus 1995). In studies on viewer preferences, Garbinger (1984, 1987, 1993) found that readers prefer shorter lines of text especially for single line spacing between lines. As the line becomes longer, it becomes increasingly difficult for the eyes to sweep to the start of the next line. Line spacing of one to one-and-one-half times the type size (Galitz 2002) is recommended to differentiate between lines. Too little line spacing will cause letters from the line above to join or touch the letters on the line below and disrupt the flow of the reading.

Color

Color is a powerful visual element and can enhance the communicative effectiveness and retention of the message to the user. Performance can be enhanced considerably when color is used strategically to support task and aid in decision making (Christ 1975). Conversely, arbitrary use of color can reduce the usability of the visualization. Color can be described in terms of three dimensions: hue, value or intensity, and saturation or chroma. Hue is the spectral wavelength composition of the color consisting namely red, orange, yellow, green, blue, and violet. Value or intensity is the relative amount of lightness or darkness of the color which ranges from black to white (Galitz 2002). Saturation or chroma is the purity of the color which ranges from grey to the most vivid variant of the color (Galitz 2002).

Color Discrimination

Color is more effective than other cues such as shape, size or brightness for search tasks and symbol identification tasks. (Christ 1975). As the density of symbols in the display or the number of non-target symbols increases, the performance advantage of color coding increases (Christ 1975). The number of colors should be no more than four to five colors spaced far apart on the color spectrum for tasks that require color memorization and absolute discrimination (correct identification of color while no other color is in the field of view (Galitz 2002)).

Color Associations

The use of color should conform to the conventions used in the job and the culture of the users. Table 1 shows some of the colors that have been commonly associated with particular meanings (Galitz 2002). Unintended interpretations may arise when the color conventions are assigned other meanings. Task performance may also be affected as the color conventions are ingrained in the behaviour of the users and difficult to unlearn. For example, using other colors than blue to represent own units in military displays may cause confusion in interpretation among the military users.

Table 1: Common color associations

Color	Associated meanings	Color	Associated meanings
Red	Stop, fire, hot, danger	Blue	Cold, water, calm, sky, neutrality
Yellow	Caution, slow	White	Neutrality
Green	Go, OK, clear, vegetation, safe	Grey	Neutrality

Color Consistency and Redundancy

Color coding should be applied consistently throughout the visualization to reduce cognitive efforts and errors in interpreting the meanings of the colors for different contexts. When important information is being communicated, color should be supported by another redundant cue. This is to facilitate users with anomalous color vision to identify the important information other than color discrimination. It has also been shown that redundant coding enhances performance (Christ 1975).

Colors to Avoid

Opposing colors (yellow and blue, or red and green), highly saturated colors, and colors far apart on the color spectrum (for example red and green) may cause afterimages and shadows when used heavily on the same display or across displays (Galitz 1985, ISO 1988). The use of pure blue should be avoided for text, thin lines and small shapes (Galitz 2002) due to poor visual acuity for shorter wavelength of the visible spectrum. Insensitivity to blue also increases with age (Murch 1987). ISO (1988) recommends avoiding saturated blue for text on dark backgrounds.

Data Graphics

Data or statistical graphics refers to the presentation of data in graphical form. Common types of data graphics would include bar graphs, line graphs, scatterplots, and pie charts. Data graphics can present patterns or trends in data clearly and quickly. They also enable identification and comparison of data values.

Data-ink Ratio

Data-ink is defined as the essential non-erasable ink (pixels) used to present the data. The goal is to achieve the highest possible data-ink ratio (Tufte 1983) without removing information necessary for effective communication. This is achieved by removing the non-data-ink (pixels) that fails to present data information and enhancing the data-ink (pixels). Figure 1 shows a revised graph (on the right) after erasing half the frame (remove non-data-ink) and increasing the data curve (enhance the data-ink) (Tufte, 1983).

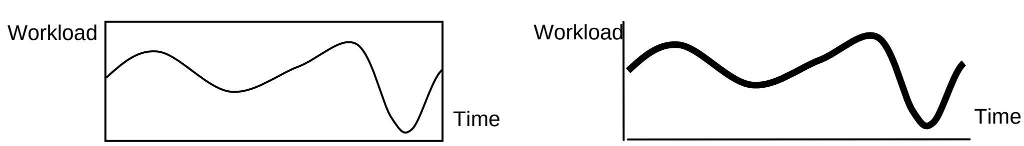

Figure 1: Graphs of different ink-ratios

Moiré Effects

Moiré effects occurs when the users view a set of lines or dots that is superimposed on another set of lines or dots, where the sets differ in relative size, angle, or spacing. This produces distracting appearance of movement and should be avoided (Tufte 1983).

Grid and Rules in Tables

The grid should be muted relative to the data so that its presence does not compete with the data. This is achieved by: (1) making the grid thinner; (2) making the grid dotted; and, (3) using a grey grid. Dark grid lines should not be used as they interfere the reading of the graph and interpolating the data (Tufte 1990). In creating tables the use of rules should be avoided unless they are absolutely necessary. Vertical rules are needed only when the space between columns is so narrow that mistakes will occur in reading without rules. Thin rule should be used rather than thick rules (Tufte 1990).

Small Multiples Design

Small multiples refers to information slices that repeat a common design several times within a user's eye span—with each instance showing different data values (Tufte 1990). Their multiplied smallness allows local comparisons at a glance and the consistent design facilitates the users to compare and contrast the change in data. In Figure 2, each multiple on the lower portion of the figure maintains a consistent frame of reference—size, color, fonts—with changing data—cloud shape, number of minutes. This provides a visual appreciation of how the storm (or information displayed) changed over time.

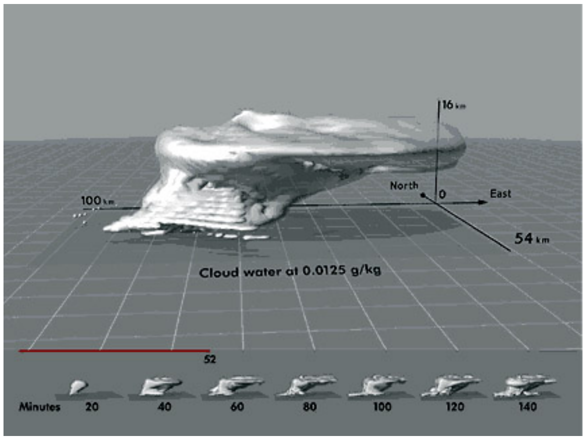

Figure 2: Small multiples showing change of shape of the storm (Baker & Bushell, 1995)

Number of Colors

The number of colors for data graphics should not be more than six (Galitz 2002) to minimise confusion and distraction in looking at the visualization. Variables should be encoded in different hues for tasks that require efficient discrimination of colors (Cleveland 1994).

Effectiveness of Visual Variables

Bertin (1983) provided a comprehensive survey of mapping the graphical data representation (components) into visual variables (position, size, value, texture, color, orientation, and shape) and the rules governing their effective use. The type of data to be represented in information visualization can be classified into the ordinal, nominal, and quantitative.

Cleveland and McGill (1984) broaden Bertin's work by identifying several other visual variables and ranked them according to different effectiveness for quantitative data. MacKinlay (1986) extended Cleveland and McGill's ranking to include ordinal and nominal data as shown in Table 2. Although MacKinlay's ranking is not empirically verified, it provides a guide to selection of visual variables for effective representation of different data types in information visualization.

Table 2: Ranking of visual variables for different data types (MacKinlay, 1986). The variables in the grey boxes are not applicable for that data type.

Qualitative	Ordinal	Nominal
Position	Position	Position
Length	Density	Color Hue
Angle	Color Saturation	Texture
Slope	Color Hue	Connection
Area	Texture	Containment
Volume	Connection	Density
Density	Containment	Color Saturation
Color Saturation	Length	Shape
Color Hue	Angle	Length
Texture	Slope	Angle
Connection	Area	Slope
Containment	Volume	Area
Shape	Shape	Volume

Visual Perception

Norman (1993) discussed several basic principles for the development of effective visual representations which we discuss next. First, the Naturalness Principle states that experiential cognition is most effective when the properties of the visual representation map closely against the properties of the information being represented. This principle suggests that artificial visual representations that vastly differ from the information being represented can actually have a negative effect in perceptual understanding.

The Perceptual Principle states that perceptual and spatial representations are preferred over non-perceptual, non-spatial representations, but only if the Naturalness Principle is followed. This principle suggests that visual representations that require reflection are not as rapidly understood and perceived as those that can be used experientially, through simple graphical perceptual comparisons.

The Appropriateness Principle states that visual representations should provide just sufficient information that is required for the task. This principle suggests that additional information not related to the task at hand should be avoided, as it may actually cause distractions.

Tversky et. al. (2002) also discussed two basic principles: Principle of Congruence and Principle of Apprehension. The Principle of Congruence states that the structure and content of the external representation should correspond to the desired structure and content of the internal representation. This principle suggests that visual representations should match and represent the information presented. The second principle, the Principle of Apprehension, states that the structure and content of the external representation should be readily and accurately perceived and comprehended.

In addition to these aforementioned basic principles, visual perceptual theories have also suggested how the human visual system perceives structures and groups of information from the scene. By exploiting the visual perception capabilities of the human it is possible to map data to visual representations that will improve visual tasks such as pattern matching, trend identification, recognizing gaps and error discovery.

Extending these basic principles and theories, the following sub sections will discuss and list out guidelines pertaining to pre-attentive vision processing, attentional cueing, gestalt principles of organization and depth perception theory that can be considered for information visualization design.

Pre-attentive Visual Processing

Research in vision and psychology has discovered that the human low level visual system rapidly processes information in parallel to extract basic visual features of objects in a scene. These are simple shapes and colors that “pop out” from their surroundings. The theoretical mechanism underlying the pop-out phenomenon is called pre-attentive processing as it occurs prior to conscious attention. The visual features that are pre-attentively processed can be organized into a number of categories based on form, color, motion, and spatial position. A survey of these features can be found in (Healey and Enns 1999).

Experimental studies in the development of scientific visualizations have indicated that such features can be mapped to critical information to support visual cognitive tasks such as target detection, boundary detection, and region tracking at a single glance for rapid perception (Healey 1993). Appendix A describes empirically tested guidelines that explain how such pre-attentive features can be used for designing and developing advanced visualizations techniques for supporting the above mentioned visual cognitive tasks.

Attentional Cueing

If we say we are going to “cue” attention, we must begin by defining visual attention, and how it works. When we say that one is attending to a location, we are talking about selective attention. That is, selectively filtering out unnecessary information in order to make more efficient use of the vast array of available information. Selective attention research has a very long history, dating all the way back to James (1890), who some consider a founding father of experimental psychology.

One may then ask what are you studying when you say “attention” and “selective attention”? Posner (1990) answers this with: “Attention involves selection of higher levels of processing, including conscious processing, while preventing access of other signals to those same high levels of processing. Selective attention plays an important role in most cognitive tasks including pattern recognition, reading, and mental imagery.”

More recently, theories of visual attention have fallen into two distinct camps, space-based and object-based theories. Logan (1996) outlined these two theories as follows. Space-based theories argue that attention is distributed over visual space, irrespective of the objects (stimuli) in this space. These theories often assume that attention is like a spotlight moving around in visual space. When an object is "in" the spotlight, it is attended to, if not it is ignored (Eriksen & Eriksen, 1974; Eriksen & St. James, 1986; Posner, 1980; Posner & Cohen, 1984; Treisman & Gelade, 1980; Treisman & Gormican, 1988).

On the other hand, object-based theories assume that objects are selected, rather than areas of visual space (Kahneman & Henik, 1981; Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992; Pylyshyn & Storm, 1988). These theories assume that representations of visual space are organized according to the Gestalt laws of perception. In other words, objects are attended to as a result the Gestalt laws “focusing” attention. For example, two objects that are near each other may be attended to due to their proximity. On the other hand, objects that are not spatially adjacent may be attended to quite well if they are similar.

As can be seen, there is abundant research supporting both theories. However, Logan’s (1996) model of visual attention accounts for both theories implying that perhaps both approaches are used by the brain depending upon the situation. Perhaps more pertinent to this discussion is the fact that both theories allow us to understand more completely how visual attention functions.

However, in a C2 display we are more interested in cueing attention to a certain location in visual space. In this case, the dichotomy lies between endogenous and exogenous visual attention (Briand & Klein, 1987; Posner, 1980). Specifically, exogenous attention is an automatic response to an external cue. A typical exogenous cue would be a bar near a peripheral target. For example, Henderson (1991) used a bar that underlined a target to be reported, while Murphy & Eriksen (1987) used a bar that pointed at a target.

Endogenous visual attention, on the other hand, is under more voluntary control and the cues used in this case refer to locations that are predicted to contain a target. A typical endogenous cue would be a line or arrow at fixation that points to where attention should be directed (e.g., McCormick & Klein, 1990; Posner, et al, 1980).

Perceptual Organization

Gestalt psychologists were intrigued by the way the human mind perceives wholeness out of incomplete elements (Behrens 1984; Mullet and Sano 1995) and proposed a theory of pattern perception that relies on the overall form and is not predictable by considering the sum of its components. Factors that impact on the perception of form and how parts are grouped into structural forms are captured in what are called the "Gestalt Principles of Organization". Gestalt principles describe how elements presented together tend to be grouped into distinct patterns. In essence, Gestalt principles can be applied as abstract information visualization design guidelines for tasks showing relationships that describe how information should be organized or grouped so that critical structures and relationships can be easily perceived. By mapping the information structures to easily perceived patterns, it is easier to interpret the relationships as well as the structures of the information. The information structures will also be easily interpreted when they are mapped to readily perceived patterns. There are in general 9 Gestalt principles of organization that can used as guidelines for the design of information visualization which are shown in Appendix B.

Depth and 3D Perception

Depth perception is the visual ability to perceive the world in 3D and gives humans the ability to gauge the distance to an object. There are 3 categories of depth cues being researched in the domain of depth perception: monocular static cues, monocular dynamic cues, and binocular cues. Monocular cues are produced by the input of one eye, while binocular cues are produced by the input from both eyes. Appendix C describes guidelines that explain how depth cues can be used for designing and developing advanced visualizations techniques.

Human Memory

In this section we discuss the cognitive factors that come into play when designing for C2 information displays in terms of human memory. One might easily assume that interacting with a display assumes no need for memory but as we will see that is not always the case. In general memories are first encoded (processed by the senses and sent to the brain), then stored (through various physiological processes in the brain), and finally retrieved. In terms of this discussion we will only elaborate on encoding and retrieval as they are most germane to the discussion.

Sensory Memory

Memories can be encoded into three different types of memory; sensory, short term, and long term memory. We will discuss each next in turn. Sensory memory takes place and lasts on the order of seconds and the classic example is Sperling's (1960) partial report technique. In his experiments participants were shown three rows of four letters each for a brief time (e.g., 150 ms.). If they were told to report all the letters they performed poorly and reported only 4-5 letters. However, if they were given an auditory tone (high, medium, or low) corresponding to the row to report they then reported on average three of the four letters. This showed that the whole array must have been in a sensory store and the letters were all briefly available to be reported as the participants did not know ahead of time which row they were to report.

Short Term Memory

Short term memory is less fleeting and is most well known from Miller's (1956) seminal paper that showed participants were able to remember 7 plus or minus 2 chunks of information. For example, if a list of ten numbers was read, a participant on average would be able to recall between five and nine numbers. The term chunk refers to the fact that if pieces of information are put together into a meaningful whole, then more can be recalled. For example, most people can easily remember five; if not more, telephone numbers, which with area code, five phone numbers is a combined total of 50 numbers recalled.

Baddeley and Hitch (1974) proposed a model that extended the idea of how short term memories are encoded and processed with their working memory model in which it has been shown that participants can use either a "verbal store" (rote rehearsal) or a "visual-spatial sketchpad" (used for visual memories). Others have extended the idea of visual memories (see Kosslyn, 1980) further showing how non-verbal memories are encoded.

Long Term Memory

Long term memory is that memory store that holds information for anywhere from hours to years. Anderson (1976) explains that long term memory is broken down into two distinct types termed declarative and procedural. Declarative memories are those that take into account facts (semantic) and personal memories (episodic). Procedural on the other hand takes into account procedures we learn (e.g., motors skills such as driving a car). The main difference between declarative and procedural is that procedural memories are termed implicit memory, meaning that no conscious recall of the information is needed; unlike declarative memories in which one has to recall the information (sometimes with great effort).

Relations to C2 Information Display Design

In general, most of the information given to a user would fall under sensory information as all they need to do is encode and act upon the information. However, memory does interact to a large extent with previously discussed attentional aspects of perception and more recently several papers have discussed the relation of attention to working memory (Cowan, et al, 2005; Cowan and Morey, 2006). It seems that attention helps in the encoding of working memory and the two may be intimately related.

A second aspect of memory that has been given prominence lately is that of prospective memory. The term was first used by Meacham and Singer (1977) and describes the act of remembering to do something in the future. For example, an air traffic controller puts several airplanes into a holding pattern due to weather and an already increasing cue of prior traffic still waiting to land. Prospective memory studies how the controller must remember to eventually take those planes out of the holding pattern. In terms of C2 displays, one can easily see the relevance of prospective memory especially if one is building a tactical plan and needs to wait until event A occurs before event B can be accomplished. Similarly, if one has several tasks to perform using a display, one of them may be to refer back to a certain area, troop movement, etc., and react if a certain event occurs.

Perception Based Evaluation Techniques

The information mapped by visualizations must go through the human perceptual system, thus careful attention during evaluation to the perceptual system's characteristics can greatly improve the effectiveness of visualizations (Rushmeier, et al, 1997). The evaluation of the effectiveness of visualizations can substantiate claims made about the value of a new technique, and enables the performance of comparisons with current established systems. This section adopts a task-oriented pipelined approach to describing the evaluation methods.

Situation Awareness

One of the main objectives of information visualizations is to enable a user to perceive and comprehend the environment and the dynamics behind it, of the past, present, and future such that action can be taken. This is situation awareness (SA), a mental representation of the current state of a dynamic environment. Endsley (2000) characterizes situational awareness into three levels: Perception, Comprehension, and Projection, which captures the essence of SA.

In the context of C2 systems for military applications, situation awareness enables a commander to Perceive and Comprehend enemy troop movement, deployment, formation (i.e. unit type: artillery, armour, infantry, etc) and concentrations such as to possibly predict (Projection) enemy tactics, and to hence plan his own tactics to pre-empt the enemy, and is thus an important subjective measure in an evaluation of how well an information visualization performs.

A visual task based evaluation framework

The evaluation of an information visualization system (IVS) is essentially the evaluation of how well the user performs tasks in the system (Hollands, 2002; Juarez, 2000). As such, this paper adopts a model-based evaluation framework, which models the visual tasks that a user performs.

Some common evaluation techniques which apply to information visualization are the *checklist* – which usually has a limited response outputs of accept/reject, *questionnaires/interviews* – which incorporate some form of subjective valuing, *observational techniques* – which measure behaviour directly and thus are limited to only behavioural variables and finally *experimental techniques* – which is by far the most common and rigorous means of scientific evaluation. These techniques are all applicable to the proposed visual task based evaluation framework, and depend on the extent of evaluation required by the evaluator as is balanced by resources available and requirements.

The following two sub-sections delineate the possible visual tasks that users may perform on both a low and high level of human perception. They serve as a guide to what users may be tasked to perform in order to apply the above evaluation techniques to quantify and qualify the output responses of the users.

Low level visual tasks

Wehrend and Lewis (1990) describe a low level, domain-independent taxonomy of tasks that users could perform in a visual environment. Their taxonomy is useful in suggesting possible tasks that could be used for evaluating different pre-attentive components in the system. Possible output data measured may include time or accuracy to locate the information. The tasks are described below.

- **Locate**
  Searching for semantic units is one of the most rudimentary tasks required for interaction in an IVS.
- **Identify**
  The Identify task is similar to Locate, with the main difference being that the semantic unit may not be one that the user has prior knowledge of.
- **Distinguish**
  Semantic units can sometimes be designed with similar graphical layouts or values. This may be for the purposes of identifying that they may or may not belong to a common group.
- **Categorize**
  Users can be tasked to arrange/organize semantic units such as to follow particular characteristics such as shape or color such as to exploit human spatial memory.
- **Cluster**
  Users can be tasked to move semantic units together into groups. This is different from a categorize task as grouping need not depend on similar characteristics.
- **Distribution**
  Users can be tasked to separate semantic units into various areas of the display.
- **Rank**
  Users can be tasked to rank semantic units according to a set of conditions (e.g., population density, death rates), and is only applicable to scalar and ordinal data.
- **Compare within entities**
  Users are tasked to determine an outcome based on the attributes of similar objects.
- **Compare between relations**
  Comparing between relations refers to the task of comparing attributes between different objects. It is an inferential task to derive both relational and non-relational aspects of the attributes.
- **Associate**
  Association calls upon the user to determine which objects in the display are related and to annotate as such. This is different with the Compare between relations task as it is not necessary to determine an outcome of the relation.
- **Correlate**
  A correlation task determines how well the user is able to discern objects which share attributes with other objects.

High level visual tasks

Knowing the fundamental interaction tasks is insufficient to describe the means by which humans perceive and cognize. Zhou and Feiner (1998) propose a visual task taxonomy that is based on cognitive psychologists' extensive studies (Treisman, 1982; Levie, 1987) to understand human visual perceptual behaviour, as well as Wehrend and Lewis's (1990) work that provides a good visual task framework to evaluate information visualizations.

Zhou and Feiner (1998) characterize visual tasks into visual accomplishment and visual implications:

> "Visual accomplishments describe the type of presentation intents that a visual task might help to achieve, while visual implications specify a particular type of visual action that a visual task may carry out" (ibid).

Visual task classification through visual accomplishment is inadequate. This is because visual accomplishment is domain *dependent*, and relies on the intent of the presentation and the visual tasks. Take for example, the blueprints of a house as presented to an architect and a structural engineer; while the intent of the presentation of the blueprints to the architect is of aesthetics and ergonomics, the intent to the structural engineer is for stability and strength of materials used.

Visual implication on the other hand is domain *independent*, since it does not take into account the presentation intent but rather, the visual actions that each task may carry out. Zhou and Feiner formulated 3 types of visual perception and cognitive principles: visual *organization*[1], *signalling*[2] and *transformation*[3].

Table 3: Zhou and Feiner's (1998) visual implication framework as presented in (Morse, Lewis, and Olsen 2000)

Visual Implication	Type	Subtype	Elemental tasks
Organization	Visual grouping	*Proximity*	Associate, cluster, locate
		Similarity	Categorize, cluster, distinguish
		Continuity	Associate, locate, reveal
		Closure	Cluster, locate, outline
	Visual attention		Cluster, distinguish, emphasize, locate
	Visual sequence		Emphasize, identify, rank
	Visual composition		Associate, correlate, identify, reveal
Signalling	Structuring		Tabulate, plot, structure, trace, map
	Encoding		Label, symbolize, portray, quantify
Transformation	Modification		Emphasize, generalize, reveal
	Transition		Switch

From Table 3, this high level visual task framework provides a better model of how the human perceptual and cognitive systems work than the elemental tasks given above. This high level framework gives a better fit for the proposed evaluation methodology.

[1] *Visual organization* suggests how people organize the world and perceive it as a coherent whole.
[2] *Visual signalling* explains how people tend to interpret visual cues and infer their meanings.
[3] *Visual transformation* explains how people switch attention and adapt to visual changes.

Evaluation can now take the form of questioning (through the application of the evaluation techniques) how well visual grouping, visual attention, etc. is enabled in the IVS, which subtend the elemental tasks. This taxonomy thus provides a comprehensive and complete evaluation of information visualizations.

How to Apply to C2 Information Displays

The question that arises from this entire discussion is: "How does one apply this to the design of a C2 display?" We argue that one need not apply the entire set of guidelines en masse but rather they should be used more as a reference to check the ideas that are put forward in the design of an information display. For example, one could refer to the section on Data Graphics when designing small informational graphics to be used on a display. Here one can get guidelines for the best way to design data graphics as well as find references if more information is needed.

Likewise an already existing information display could be evaluated in terms of the guidelines set forth here and used as a checklist. One example might be an evaluation of the attentional cueing components designed into a display. Here one could reference back to the section on Attentional Cueing and evaluate if the techniques being used are efficient and will indeed cue attention as needed. For example, a review of endogenous and exogenous cues and their definition may help one design, or modify the design, of an existing cueing system.

What if one wants to build a system from the ground up? How would these guidelines be used then? In this case we would argue three points. First, no one truly builds a system from the ground up without any prior knowledge of a similar system. Further, any similar system will be known to have good and bad features of which these will be taken into account in the design of the new system. Second, when building a system from the ground up there will be separate components that may be tested by themselves before being added into the system as a whole. Finally, this set of guidelines is not intended to be an exhaustive list of all issues dealing with information displays. In fact, a well coordinated team will have a good mix of multidisciplinary backgrounds so that their foundations may be incorporated and lastly one must somehow test the system before fielding.

This leads to the final question: "How does one test a visual information display?" While this is quite an open-ended question we suggest the following points. First, as previously mentioned it is much easier to test individual components to assess their utility and fine-tune their workings before putting them into the system as a whole. For example, one can easily test attentional cues in a simple environment, changing them as necessary to work in the operational environment. Secondly, testing components allows one to use naïve participants who do not need to understand the final product but can be used to test important factors such as legibility, color recognition, etc., before the system is shown to the end-user. In fact, the final product may be tested with naïve participants to get an understanding of potential training requirements as they (the naïve users) have no preconceived idea of how, what, when, where, or why things are supposed to be done. Finally, the last step would be to test in a semi-or full-operational environment with actual end-users. In this case one is less likely to be performing specific empirical experiments, and more likely to be observing the user and understanding their likes and dislikes with the system. Objective measures can be recorded, but often one is not able to run enough trials to be able to perform a statistical analysis with out referring to little-known (but acceptable) statistics for small-n designs (for an excellent review of statistics for single-case and small-n experimental designs see Todman and Dugard, 2001).

Overall, an attempt has been made to present a set of overarching guidelines for use in the design of a C2 information display. Several issues have been outlined ranging from graphical design to experimental psychology and suggested ways in which these guidelines should be used were given. Finally, issues dealing with how one might be able to test a C2 information display were discussed.

Acknowledgements

The authors wish to thank the Department of Defence of the United States of America and the Ministry of Defence of the Republic of Singapore for supporting the joint research and development of cognitive based information visualization design guidelines under the project agreement concerning Multi-dimensional Battlespace Visualization (MBV).

The authors also wish thank the research members of AFRL/HECV – John McIntire, George Reis, and Eric Heft; as well as and Ricky Chng, Aaron Zhang and Kenny Choo of the DSO/HFL for supporting the MBV research and development.

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Appendix A: Empirically tested guidelines on pre-attentive features for designing and developing advanced visualizations techniques.

<table>
<tr><th>Pre-attentive Task</th><th>Pre-attentive Feature</th><th>Guidelines</th></tr>
<tr><td>To identify form, shape and detailed patterns of visual objects</td><td>Color</td><td>Use a sequence with a substantial luminance component (i.e. black and white) in order to assist the individual to interpret detailed information of the visual object.

Use different levels of saturation to encode different categories of visual object.

Do not use more than 5 colors. Avoid hues like turquoise and lime green, as they are perceived more ambiguously (Kosara, Healey, Interrrante, Laidlaw and Ware 2003).</td></tr>
<tr><td rowspan="5">To detect a target</td><td>Flicker</td><td>Flicker must be coherent. If there are more than two flickering objects, they must flicker at the same rate. The cycle length has to be 120 ms or greater for preattentive detection (Huber and Healey 2005).</td></tr>
<tr><td>Velocity</td><td>Higher initial velocity produces a faster response to changes in velocity. If an object has a velocity of 100 pixels per second (pps), the detection of a change to 10 pps is much faster than an object with initial velocity of 20 pps. When the target velocity is double of its initial velocity, detection is preattentive (~50 ms) (Hohnsbein and Mateeff 1998).

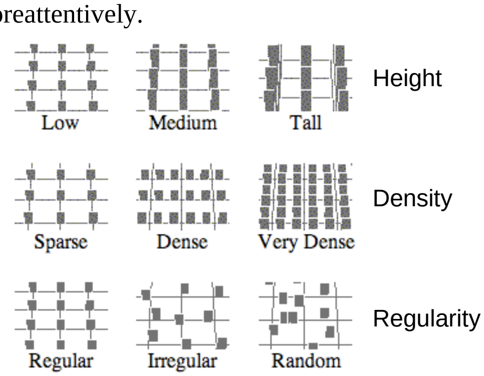
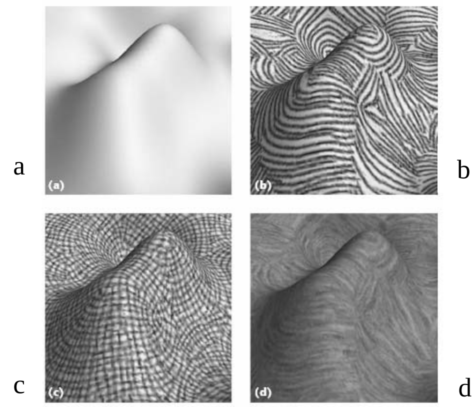
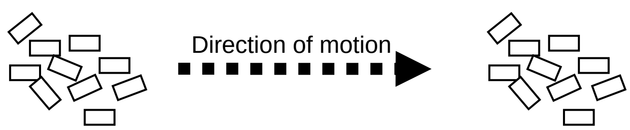
There must be a minimum of 16 pps change difference between initial and current velocity for the viewer to detect a change preattentively (Huber and Healey 2005).</td></tr>
<tr><td>Direction of Motion</td><td>Direction of target object must differ by at least 20° to be detected (Huber and Healey 2005).</td></tr>
<tr><td>Texture</td><td>Height and density can be used to form texture patterns that can be identified preattentively as shown in Figure 3. However, regularity can only be used as a secondary dimension. It is recommended to use height to represent primary dimension, as height can be identified at preattentive exposure durations (150 ms or less) with very high accuracy (~93%). This is independent of background density and regularity patterns. Even if the background density or regularity patterns are modified, the viewer will still be able to detect target objects by height preattentively.


Figure 3: Different components of texture: height, density and regularity.</td></tr>
<tr><td>Color</td><td>It is recommended to use color for rapid target detection (~50 and 100 ms detection). Maximum of 7 isoluminant (same luminance or intensity of light) colors can be displayed simultaneously while still allowing for the rapid and accurate identification of any one of the seven (Healey 1993). Suggested colors are green, yellow, orange, red, and purple.</td></tr>
</table>

Pre-attentive Task	Pre-attentive Feature	Guidelines
To enhance the perception of a visual object's 3D shape.	Texture	It is recommended to render a three dimensional (3D) image using line integral convolution (see Figure 4d) which will give the best perception of 3D shape, instead of Phong shading (see Figure 4a). The other methods are rendering the 3D image using one principal direction and two principal directions, as shown in Figure 4b and Figure 4c respectively (Kosara et al., 2003).  **Figure 4: Various 3D rendering that can be used to enhance the surface perception of a visual object.**
To track a particular region	Direction of Motion	Coherent motion can be used to separate elements into coherent groups (Nakayama and Silverman 1986). In other words, if a particular group moves in the same direction, the individual will be able to preattentively detect its motion and thus the region. Even though the objects have different orientation, when they move in the same direction, the individual will be able to detect the region preattentively (seeFigure 5). Oscillation of target objects must also be in phase/coherent (Driver, et al, 1992).  **Figure 5: When the visual object moves in the same direction, orientation will not affect the user in detecting the region preattentively.**
	Color and Texture	Color and texture can be combined in a single display only in cases where the texture targets have a strong perceptual salience, i.e., they are taller and denser (Snowden 1998). It is recommended that color is used to represent primary data while texture is used to represent secondary data. This is because color variation interferes with an observer's ability to see texture regions based on height or density, but variation in texture has no effect on region detection by color.

<table>
<tr><th>Pre-attentive Task</th><th>Pre-attentive Feature</th><th>Guidelines</th></tr>
<tr><td rowspan="3">To detect boundary</td><td>Color and Form</td><td>It is recommended that color is used to represent the primary data, and form to represent the secondary data. This is because visual system assigns a higher importance to color than to form during boundary detection. Thus, a random color interferes with form boundary detection, but a random form has no effect on color boundary detection (Callaghan 1989).

If color and form are used for real-time visualization, the sequence of frames should be displayed at 10 frames per second for accurate boundary detection.

For accurate and rapid detection of form, color must be held constant. Otherwise, color would be a better feature to be used for boundary detection.</td></tr>
<tr><td>Color and Intensity</td><td>It is recommended that intensity is used to represent the primary data and color to represent the secondary data. This is because visual systems assign a higher importance to intensity than to color during boundary detection. Thus, a random intensity interferes with hue boundary detection, but a random hue has no effect on intensity boundary detection (Callaghan 1984).

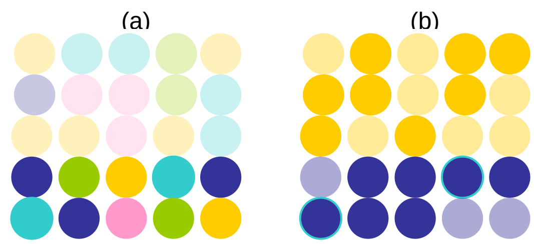



Figure 6: Even though color is random in (a), boundary can still be detected preattentively because the visual system assigns a higher importance to intensity. In (b), when the intensity is random, it becomes more difficult to detect the boundary using color.</td></tr>
<tr><td>Color and Orientation</td><td>When two independent data values are shown on a single display, they should be represented by color and orientation. Color and orientation will not cause any visual interference unlike its counterparts, i.e., color and intensity or color and form (Healey, et al, 1993). Boundary can be detected preattentively either by orientation or color as shown in Figure 7.

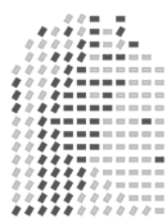
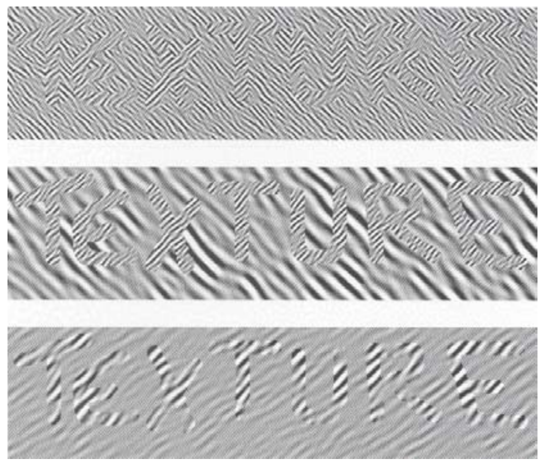
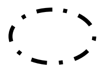
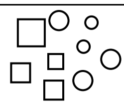
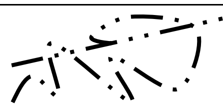
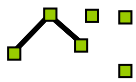
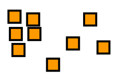
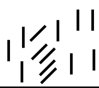
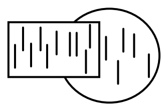



Figure 7: Orientation and color can be used simultaneously to represent data preattentively without affecting each other.</td></tr>
</table>

Pre-attentive Task	Pre-attentive Feature	Guidelines
To identify segmentation of regions	Texture	Any given texture can be perceived to be different depending on the background, thus making texture contrast the strongest visual cue for texture segmentation. The orientations of differing textures should differ by at least 30° (Blake and Holopigan, 1985). However, orientation is limited and should not be used as a primary means for texture segregation. The difference in texture frequency should be at least 3 or 4 times (Wilson and Bergen, 1979). E.g. assuming 2 layers of textures with frequencies f_1 and f_2, either $f_1 > f_2$, or $f_2 > 3f_1$ will suffice for the different textures to be segmented by the human visual system. See Figure 8 below for several examples.  **Figure 8: Top: Only texture orientation is altered, weakly distinguishing the word TEXTURE. Middle: Texture orientation and size are altered, strongly distinguishing the word. Bottom: Texture contrast is altered, strongly distinguishing the word (Ware 2000).**

Appendix B: Gestalt principles.

Gestalt Principle	Example Figure	Verbal Descriptor
Law of Simplicity		Every object is perceived in a way that the resulting structure is as simple as possible.
Law of Closure		Tendency to close gaps and complete unfinished objects.
Law of Similarity		Elements which look similar (example, size, color, orientation, velocity and shape) are perceptually grouped together as a object
Law of Good Continuity		Elements that are smooth and continuous are perceptually grouped together than ones that contain abrupt changes in direction.
Law of Connectedness		Elements that are physically connected are perceptually grouped together as a object.
Law of Proximity		Elements that are close together are perceptually grouped together as a object
Law of Common Fate/Common orientation		Elements with the same moving direction or orientation are perceptually grouped together as a object
Law of Balance/Symmetry	<< >>	Elements in symmetrical alignment are perceptually grouped as a object
Law of Common Region		Elements tend to be group if they are located within a common region. The closed contour tends to be perceived as the boundary of the object.

Appendix C: Guidelines for the use of depth cues.

<table>
<tr><th>Category</th><th>Depth Cue</th><th>Guidelines</th></tr>
<tr><td>Monocular Static</td><td>Perspective Based Cues</td><td>Linear perspective is widely regarded as one of the most effective sources of depth information (Hone and Davies, 1995). Figure 9 illustrates an example of linear perspective.

Figure 9: Linear perspective as one of the most effective depth cue.

Converging parallel lines should be used to give an impression of increasing distance.
Similar objects should appear smaller with increasing distance.
Texture elements of uniformly textured surfaces should appear smaller with increasing distance.
Linear perspective should be avoided when there is a need to convey precise values in volumes and area (Kosslyn et al., 1983).
Occlusion of objects can be used to provide binary depth information between objects. Objects that are further away should be occluded by objects that are nearer to the picture plane (see Figure 10).

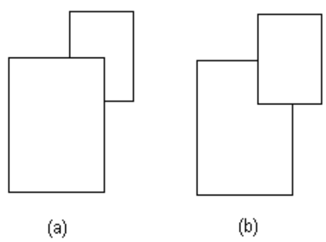
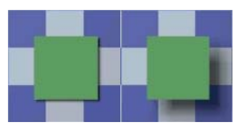
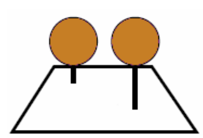


Figure 10: Depth perception based on occlusion. (a) The larger rectangle is perceived to be nearer. (b) The smaller rectangle is perceived to be nearer.</td></tr>
</table>

Category	Depth Cue	Guidelines
Monocular Static	Non Perspective Based Cues	• Focus effects should be used to separate foreground objects from background objects (Ware 2000). Nearby and distant objects should be blurred while only objects within the focal distance should be sharp (see Figure 11).  **Figure 11: The blurring effects provide visual cues to relative distance.** • Cast shadows act as a depth cue to locate an object with respect to some surface in an environment when the distance between the object and the surface is small (Madison et al., 2001) and can be used when the surface geometry is unfamiliar or complex (Haber, 1988). Figure 12 below illustrates this effect, where the object on the right appears to be nearer to the picture plane as compared to the object on the left.  **Figure 12: Similar objects perceived to be at different depths due to cast shadows.** • Artificial spatial cues such as dropping lines (see Figure 13) to some surface are also effective in providing depth information (Kim et al., 1991). Such artificial cues are functionally similar to cast shadows. However, they are interpreted much more readily as there will be no conflict with lighting directions and humans perceive lines more readily than other patterns (Chambers et al., 1983).  **Figure 13: Dropping lines to a ground plane as an effective artificial spatial cue. The left circle appears to be behind the right circle.** • Luminance and contrast have little to no effect in depth perception and therefore should not be used for portraying depth information (Hone and Davies, 1993).

<table>
<tr><th>Category</th><th>Depth Cue</th><th>Guidelines</th></tr>
<tr><td>Monocular Dynamic</td><td>Depth from Motion</td><td>Depth or structure from motion provides visual cues (location, velocity, acceleration and direction) humans pick up when objects move through an environment (Gibson 1986).

• Motion parallax should be used to convey depth information when objects move in parallel with the viewer. Objects nearer the viewing plane should appear to travel at higher velocity, whereas objects further from the viewing plane should appear to move at lower velocity (Hochberg, 1986; Wann et al., 1995).
• Kinetic depth effect can be used to create a perception of a rigid 3D object when the view of a 2D object is changed (e.g. via rotation in 3D Cartesian space) (Wallach and O’Connell, 1953). E.g. when an irregular line drawn on a 2D screen space is rotated about a vertical axis, the perception of a rigid wire bent into a 3D object is perceived.</td></tr>
<tr><td>Binocular</td><td>Stereopsis</td><td>Stereoscopic depth perception is the process that brings the retinal images in the two eyes to form one single image. During the process, the brain locates the similarities between the two individual images formed in each eye and then combines the individual differences to form the combined image (Wheatstone, 1838).

• Stereopsis diminishes rapidly with increasing distance, thus its usage should be limited to objects within the near and middle viewing fields not more than 10 meters from the viewpoint (Nagata, 1993).
• Binocular vision should be used only for comparing relative depth of objects and not for absolute or concise measurements (Gillam, 1995).
• Stereopsis is particularly useful in providing visual cues for objects in motion as humans are more sensitive to binocular disparity when objects are moving (Yeh, 1993).</td></tr>
</table>