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**Title:** Scientific and graphic design foundations for C2

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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). We will give a review of the most relevant issues in the literature as well as how the findings may be applied. For example, for graphical design we discuss the work or authors such as Tufte, Ware and Healy 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. We end by discussing a proposed method for taking into account and applying these principal for the design of an optimal C2 system.

## 1. 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: section 1 outlines the graphic design guidelines that exploit pictographic and typographic elements to enhance visual communication of information. Section 2 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. Section 3 relates issues of human memory to C2 displays. Section 4 discusses evaluation guidelines and takes a task-oriented approach to describe the evaluation of information visualization systems. Section 6 concludes by describing a proposed method for taking into account and applying these principles for the design of C2 system.

## 2. 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. Graphic design can 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, colour and data graphics that would serve as the basis in designing the visualization.

### 2.1. 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 to assist the users in perceiving and recognizing patterns in information.

### 2.2. 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 to convey information. The goal is to optimise legibility and readability of the textual context to facilitate interpretation and comprehension of the information. Legibility is defined as the ease of identification of the text while readability is defined as the ease of comprehending the meaning of the text (Mills and Weldon 1987).

Typeface refers to the name of the type such as Times new Roman or Arial and is broadly classified into two categories, serif and san serif. Serif typefaces have small non-structural details called “serifs” on the end of some of the letters while sans serif types do not. 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 (Kenzie 1998).

Different typefaces can be used to distinguish different groups of information. The number of typefaces used in the visualization should be limited to three in a maximum of three sizes (Marcus 1995). 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 different 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.

## 2.3. Colour

Colour is a powerful visual element and proper application of it can enhance the communicative effectiveness and retention of the message to the user. Performance can be enhanced considerably when colour is used strategically to support task and aid in decision making (Christ 1975). Conversely, arbitrary use of colour can reduce the usability of the visualization. Performance can be degraded when colour is used in a non-task related way (Christ 1975).

Colour can be described in terms of three dimensions: hue, value or intensity and saturation or chroma. Hue is the spectral wavelength composition of the colour consisting namely red, orange, yellow, green, blue and violet. Value or intensity is the relative amount of lightness or darkness of the colour which ranges from black to white (Galitz 2002). Saturation or chroma is the purity of the colour which ranges from grey to the most vivid variant of the colour (Galitz 2002).

2.3.1. Colour Discrimination and Identification.

2.3.2. Colour 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 of other increase, the performance advantage of colour coding increases (Christ 1975).

The number of colours should be no more than four to five colours spaced far apart on the colour spectrum for tasks that require colour memorization and absolute discrimination (correct identification of colour while no other colour is in the field of view (Galitz 2002). Good colour choices for absolute discrimination tasks are red, yellow, green, blue and brown (Galitz 2002). For tasks which require comparative discrimination (correct identification of colour while other colours in the field of view), Good colour choices for comparative discrimination tasks are orange, yellow green, cyan, violet, magenta and the colours recommended for absolute discrimination (Galitz 2002). For tasks that require fine discrimination, a black-grey-white scale is recommended as the eye is poor at perceiving colours in fine details (Galitz 2002). The recommended tonal values are black, dark grey, medium grey, light grey and white (Galitz 2002)

2.3.3. Colour Associations

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

**Table 1: Common colour associations**

| Colour | Associated meanings | Colour | 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 |

#### 2.3.4. Colour Consistency and Redundancy

Colour coding should be applied consistently throughout the visualization to reduce cognitive efforts and errors in interpreting the meanings of the colours for different contexts. For example, yellow colour should not be used to alert users and to group items on the same screen. When important information is being communicated, colour should be supported by other redundant cue. This is to facilitate users with anomalous colour vision to identify the important information other than colour discrimination. It has also been shown that redundant coding enhances performance (Christ 1975).

#### 2.3.5. Viewing angle and distance

Colour perception is dependent on the viewing angle and distance. Table 2 lists the guidelines recommended by ISO (1988) on the use of colours for viewing angle and distance.

**Table 2: Colour guidelines for viewing angle and distance**

| **Viewing angle** | **Distance** |
|---|---|
| Avoid red and green beyond 40 degrees of viewing angle | Use highly saturated colours and colours with high luminance contrast for viewing distances beyond 60 centimetres |
| Avoid yellow beyond 50 degrees of viewing angle | Avoid saturated colours on dark backgrounds for viewing distances beyond 60 centimetres |
| Avoid blue beyond 60 degrees of viewing angle | |

#### 2.3.6. Colours to Avoid

Opposing colours (yellow and blue or red and green), highly saturated colours and colours far apart on the colour 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). In addition heavy use of colours far apart on the colour spectrum may result in visual discomfort due to constant refocusing of the eyes.

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.

### 2.4. 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.

#### 2.4.1. 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).

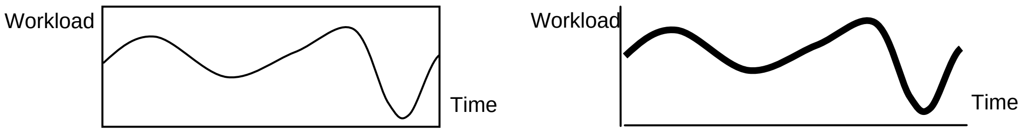



**Figure 1: Graphs of different ink-ratios**

2.4.2. 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).

2.4.3. 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 1980).

2.4.4. 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, colour, fonts—with changing data—cloud shape, number of minutes. This provides a visual appreciation of how the storm changed over time.

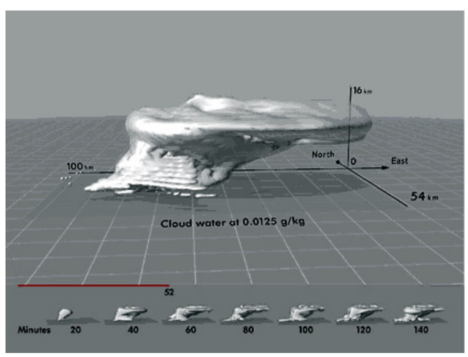



**Figure 2: Small multiples showing change of shape of the storm (Baker & Bushell, 1995)**

2.4.5. Number of colours

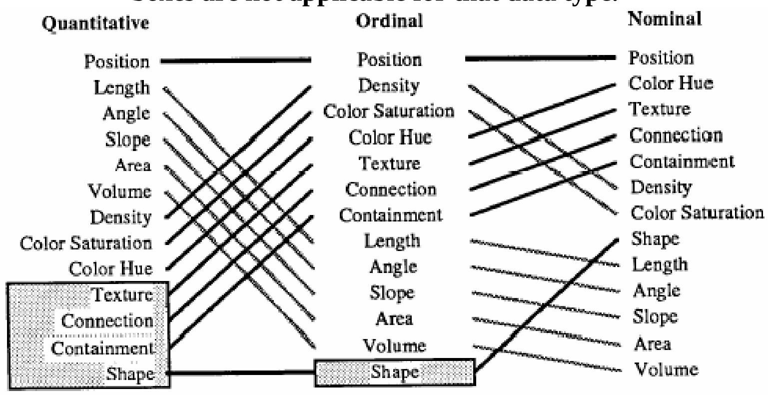
The number of colours for data graphics should not be more than six (Galitz 2002) to minimise confusion and distraction in looking at the visualization. Variables should be encoded in different hues for tasks that require efficient discrimination of colours (Cleveland 1994).

2.4.6. Effectiveness of visual variables

Bertin (1983) provided a comprehensive survey of mapping the graphical data representation (components) into visual variables (position, size, value, texture, colour, 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 (1995) extended Cleveland and McGill's ranking to include ordinal and nominal data as shown in Table 3. Although MackKinlay'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 3: Ranking of visual variables for different data types (MacKinlay, 1986). The variables in the grey boxes are not applicable for that data type.**




## 3. Visual Perception

Perceptual theories suggest 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.

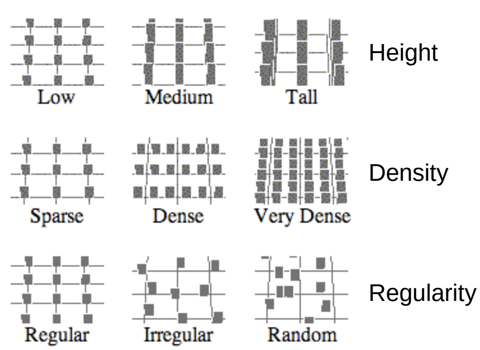
The following sub sections will discuss pre-attentive vision processing, attentional cueing, texture perception, gestalt principles of organization, depth perception theory, and guidelines that can be considered for visualization design.

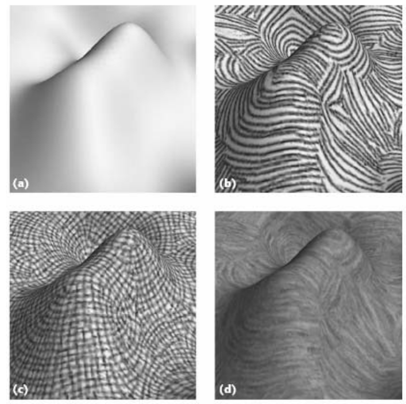
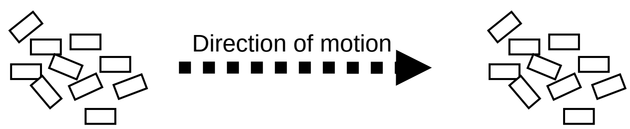
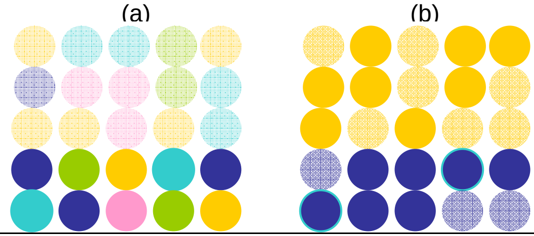
### 3.1. Pre-attentive vision processing

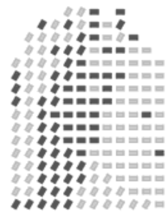
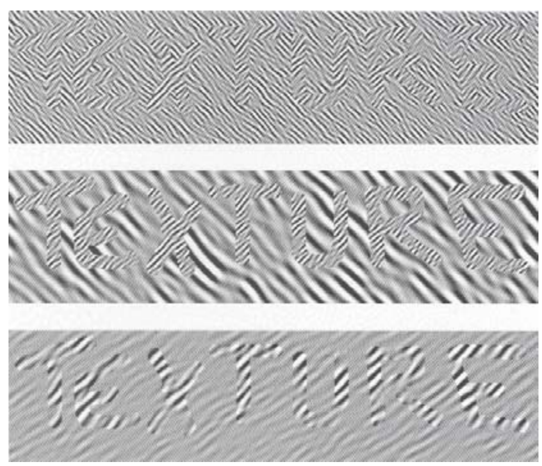
Research in vision and psychology has discovered that the human low level visual system rapidly processes information in parallel to extract basic visual features of objects in a scene. These are simple shapes and colours that "pop out" from their surroundings. The theoretical mechanism underlying the 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, colour, 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 1996). Table 4 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.

**Table 4: 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>Colour</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.<br><br>Use different levels of saturation to encode different categories of visual object.<br><br>Do not use more than 5 colours. Avoid hues like turquoise and lime green, as they are perceived more ambiguously (Kosara, 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 milliseconds 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).<br><br>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.<br><br><br><br>**Figure 3: Different components of texture: height, density and regularity.**</td></tr>
<tr><td>Colour</td><td>It is recommended to use colour for rapid target detection (~50 and 100 ms detection). Maximum of 7 isoluminant (same luminance or intensity of light) colours can be displayed simultaneously while still allowing for the rapid and accurate identification of any one of the seven (Healey 1993). Suggested colours are green, yellow, orange, red and purple.</td></tr>
<tr><td>To enhance the perception of a visual object's 3D shape.</td><td>Texture</td><td>It is recommended to render a 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).</td></tr>
</table>

| | | |
|---|---|---|
| | | <br>**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, McLoed and Dienes 1992).<br><br>**Figure 5: When the visual object moves in the same direction, orientation will not affect the user in detecting the region preattentively.** |
| | Colour and Texture | Colour 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 colour is used to represent primary data while texture is used to represent secondary data. This is because colour 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 colour. |
| To detect boundary | Colour and Form | It is recommended that colour is used to represent the primary data and form to represent the secondary data. This is because visual system assigns a higher importance to colour than to form during boundary detection. Thus, a random colour interferes with form boundary detection, but a random form has no effect on colour boundary detection (Callaghan 1989).<br><br>If colour and form are used for real-time visualization, the sequence of frames should be displayed at 10 frames per second for accurate boundary detection.<br><br>For accurate and rapid detection of form, colour must be held constant. Otherwise, colour would be a better feature to be used for boundary detection. |
| | Colour and Intensity | It is recommended that intensity is used to represent the primary data and colour to represent the secondary data. This is because visual systems assign a higher importance to intensity than to colour 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).<br> |

| | | |
|---|---|---|
| | | **Figure 6: Even though colour 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 colour.** |
| | Colour and Orientation | When two independent data values are shown on a single display, they should be represented by colour and orientation. Colour and orientation will not cause any visual interference unlike its counterparts i.e. colour and intensity or colour and form (Healey, Booth and Enns 1993). Boundary can be detected preattentively either by orientation or colour as shown in Figure 7.<br><br>**Figure 7: Orientation and colour can be used simultaneously to represent data preattentively without affecting each other.** |
| 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.<br><br>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.<br><br>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.<br><br>**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).** |

## 3.2. 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.

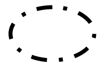
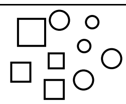
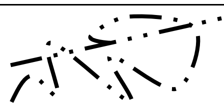
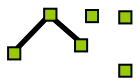
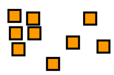
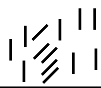
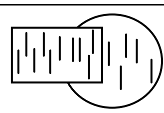
However, in a C2 display we are more interested in cueing attention to a certain location in visual space. In this case, the dichotomy lies between endogenous and exogenous visual attention (Briand & Klein, 1987; Posner, 1980). Specifically, exogenous attention is an automatic response to an external 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, Snyder, & Davidson, 1980).

## 3.3. Perceptual Organization

Gestalt psychologists were intrigued by the way the human mind perceives wholeness out of incomplete elements (Behrens 1984; Muller 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:

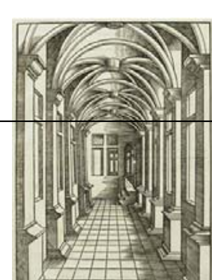
**Table 5: Gestalt principles.**

| | | |
|---|---|---|
| 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, colour, 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. |

## 3.4. 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. Table 6 describes guidelines that explain how depth cues can be used for designing and developing advanced visualizations techniques.

**Table 6: Guidelines for the use of depth cues.**

| Category | Depth Cue | Guidelines |
|---|---|---|
| Monocular Static | Perspective Based Cues | 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.  |

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- 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).

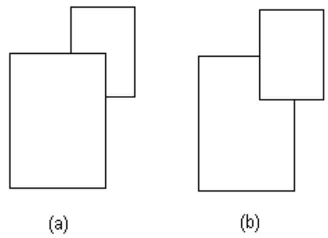


**Figure 10: Depth perception based on occlusion. (a) The larger rectangle is perceived to be nearer. (b) The smaller rectangle is perceived to be nearer.**

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<td>Non Perspective Based Cues</td>
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- 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.

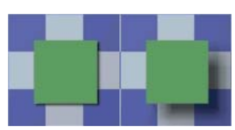
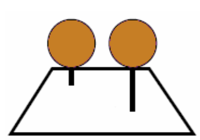


**Figure 12: Similar objects perceived to be at different depths due to cast shadows.**

- 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).



</td>
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| | | |
|---|---|---|
| | | **Figure 13: Dropping lines to a ground plane as an effective artificial spatial cue. The left circle appears to be behind the right circle.**<br><br>• 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). |
| Monocular Dynamic | Depth from Motion | Depth or structure from motion provides visual cues (location, velocity, acceleration and direction) humans pick up when objects move through an environment (Gibson 1986).<br><br>• 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).<br>• 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. |
| Binocular | Stereopsis | 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).<br><br>• 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).<br>• Binocular vision should be used only for comparing relative depth of objects and not for absolute or concise measurements (Gillam, 1995).<br>• 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). |

# 4. 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.

## 4.1. 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.

### 4.2. 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.

### 4.3. 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).

### 4.4. 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, Elliot, Saults, Morey, Mattox, Hismjatullina, and Conway, 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 a build up of prior traffic 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.

## 5. 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.

## 5.1. An visual task based evaluation framework

The evaluation of an IVS is essentially the evaluation of how well the user performs tasks in the system (Hollands and 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.

### 5.1.1. 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 colour 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.

5.1.2. 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; Goldsmith 1984; 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 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' (Zhou and Feiner, 1998).

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].

| **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 |

[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.

**Table 7: Zhou and Feiner's (1998) visual implication framework as presented in (Morse and Lewis, 2000)**

From Table 7, this high level visual task framework provides a better model of how the human perceptual and cognitive systems work than the elemental tasks given in 5.1.1. This high level framework gives a better fit for the proposed evaluation methodology.

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.

# 6. 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 section 2.4 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 section 3.2 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, colour 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.

Overall, we have attempted to present a set of overarching guidelines for use in the design of a C2 information display. We have shown issues ranging from graphical design to experimental psychology and suggested ways in which these guidelines should be used. Finally, we have addressed how one might be able to test a C2 information display.

# References


[1] Anderson, J.R. (1976) *Language, Memory and Thought*. Mahwah, NJ: Erlbaum

[2] Baddeley, A. and Hitch, G.J. (1974) Working memory. In Recent Advances in Learning and Motivation (Vol. VIII) (Bower, G., ed), pp.47–89, Academic Press

[3] Baker M.P. & Bushell C., 1995. After the Storm: Considerations for Information Visualisation. *IEEE Computer Graphics and Applications*, *15*(3), pp. 12-15.

[4] Behrens R., 1984. *Design in the visual arts*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

[5] Bertin J., 1983. The semiology of graphics. Madison, Wisc.: University of Wisconsin Press. Christ, R. E. (1975). Review and Analysis of Color Coding Research for Visual Displays. *Human Factors,* 17(6), pp. 542-570.

[6] Blake R. and Holopigan K., 1985. Orientation selectivity in cats and humans assessed by masking. *Vision Research*, 23(1), pp. 1459-1467.

[7] Briand, K.A., & Klein, R.M. (1987). Is Posner's “beam” the same as Treisman's “glue”?: On the relation between visual orienting and feature integration theory. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 228-241.

[8] Callaghan T.C., 1989. Interference and dominance in texture segmentation: Hue, geometric form and line orientations. *Perception and Psychophysics*, 46(4), pp. 299-311.

[9] Callaghan T.C., 1984. Dimensional interaction of hue and brightness in preattentive field segregation. *Journal for Perception and Psychophysics*, 36(1), pp. 25-34.

[10] Chambers J.M., Cleveland W.S., Kleiner B. and Tukey P.A., 1983. Graphical Methods for Data Analysis. Duxbury Press, Boston, Massachusetts 02116.

[11] Cleveland W.S., 1994. *The Elements of Graphing Data.* Murray Hill, N.J.: AT&T Bell Laboratories

[12] Cleveland W.S. & McGill R., 1984. Graphical Perception: Theory, Experimentation and Application to the Development of Graphical Methods. *Journal of the American Statistical Association*, *79*(387), pp. 531-554.

[13] Cockburn A. and McKenzie B., 2001. 3D or not 3D? Evaluating the effect of the third dimension in a document management system. *Proceedings of SIGCHI '99, ACM*, pp. 434-441.

[14] Cowan, N., Elliot, E.M., Saults, J.S., Morey, C.C., Mattox, S., Hismjatullina, A., and Conway, A.R.A., (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology, 51,* 42 – 100.

[15] Cowan, N, and Morey, C.C. (2006). Visual Working Memory Depends on Attentional Filtering. *Trends in Cognitive Science, 10(4)*, 139 – 141.

[16] Dix A.J., Finaly J.E. Finlay, Abowd G.D. and Beale R. *Human Computer Interaction*, Prentice Hall, 2nd Edition, pp 405-441.

[17] Driver J., McLeod P. and Dienes Z., 1992. Motion coherence and conjunction search: Implications for guided search theory. *Perception & Psychophysics*, 51(1), pp. 79–85.

[18] Eriksen, C.W., & Eriksen, C.W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*, 143-149.

[19] Eriksen, C.W., & St. James, J.D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics, 40*, 225-240.

[20] Galitz W. O., 1985. *Handbook of Screen Format Design.* Wellesley Hills, Mass: QED Information Sciences.

[21] Galitz W. O., 2002. *The Essential Guide to User Interface Design.* New York: John Wiley & Sons.

[22] Gibson J., 1986. The Ecological Approach to Visual Perception. London: Lawrence Erlbaum Associates.

[23] Gillam B., 1995. The Perception of Spatial Layout from Static Optical Information. In Epstein W. and Rogers S. (Eds.), *Perception of Space and Motion*, pp. 23-67. New York: Academic Press.

[24] Haber R.B., 1988. Visualization in Engineering Mechanics: Techniques, Systems and Issues. *Visualization Techniques in the Physical Sciences,* SIGGRAPH'88, pp. 89-111.

[25] Healey C.G., 1993. *Visualization of Multivariate Data Using Preattentive Processing.* Masters Thesis, Department of Computer Science, University of British Columbia.

[26] Healey C.G., Booth K.S. and Enns J.T., 1993. Harnessing Preattentive Processes for Multivariate Data Visualization. *Proceedings Graphics Interface '93*, Toronto, Canada, pp. 107-117.

[27] Healey C.G., Booth K.S. and Enns J.T., 1996. High-Speed Visual Estimation Using Preattentive Processing. *ACM TOCHI*, 3(2), pp. 107-135.

[28] Healey C.G. and Enns J.T., 1999. Large Datasets at a Glance: Combining Textures and Colors in Scientific Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 5(2), pp. 145-167.

[29] Henderson, J.M. (1991). Stimulus discrimination following covert attentional orienting to an exogenous cue. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 91-106.

[30] Hochberg J., 1986. Representation of motion and space in video and cinematic display. In *Handbook of Perception and Human Performance*, ed. K.R. Boff, L. Kaufman and J.P. Thomas, pp. 1-64. Wiley, New York.

[31] Hollands J.. Performance Measurement for Visualization. *Defence and Civil Institute of Environmental Medicine*, 8, Canada.

[32] Hohnsbein J. and Mateeff S., 1998. The time it takes to detect changes in speed and direction of visual motion. *Vision Research*, 38, pp. 2569-2573.

[33] Hone G. and Davis R., 1993. Brightness and Depth on the Flat Screen: Cue Conflict in Simulator Displays. *Proceedings of SPIE – Human Vision, Visual Processing and Digital Displayes IV*, Vol. 1913, pp. 518-528.

[34] Hone G. and Davis R., 1995. Brightness and Contrast as Cues to Depth in the Simulator Display: Cue Combination and Conflict Resolution. *Proceedings of SPIE – Human Vision, Visual Processing and Digital Displayes VI*, Vol. 2411, pp. 240-249.

[35] Huber D.E. and Healey C.G., 2005. Visualizing data with motion. *Proceedings of IEEE Visualization Conference*, pp. 67.

[36] ISO, 1988. *ISO Draft Standard 924X-Computer Display Colour*. Geneva: Author

[37] James, W. (1890). *Principles of psychology (Vol. 1)*. New York: Holt.

[38] Jonides, J. (1981). Voluntary versus automatic control of the mind's eye. In J. Long, & A. Baddeley (Eds.), *Attention and performance IX* (pp. 187-203). Hillsdale, NJ: Erlbaum.

[39] Juarez O., 2000. Evaluating Visualizations based on the Performed Task. *IEEE Proceedings of the International Conference on Information Visualization*.

[40] Kahneman, D., & Henik, A. (1981). Perceptual organization and attention. In M. Kubovy & J.R. Pomerantz (Eds.), *Perceptual organization* (pp. 181-211). Hillsdale, NJ: Erlbaum.

[41] Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D.R. Davies (Eds.), *Varieties of attention* (pp. 29-61). New York: Academic Press.

[42] Kahneman, D., Treisman, A., & Gibbs, B. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology, 24*, 175-219.

[43] Kim W.S., Tendick F. and Stark L., 1991. Visual enhancements in pick-and-place tasks. In *Pictorial Communication in Virtual and Real Environments*, ed. S.R. Ellis, pp. 265-282. Taylor and Francis, London.

[44] Kosara R., Healey C.G., Interrante V., Laidlaw D.H. and Ware C., 2003. Thoughts on User Studies: Why, How, and When. *IEEE Computer Graphics & Applications (Visualization Viewpoints)*, 23(4), pp. 20-25.

[45] Kosslyn, S. M. (1980). *Image and mind*. Cambridge, MA.: Harvard University Press.

[46] Kosslyn S., Pinker S., Simcox W. and Parkin L., 1983. Understanding Charts and Graphs: A Project in Applied Cognitive Science.

[47] Logan, G.D. (1996). The CODE theory of visual attention: An integration of space-based and object-based attention. *Psychological Review, 103*, 603-649.

[48] Mackinlay J.D., 1986. Automating the Design of Graphical Presentations of Relational Information. *ACM Transactions on Graphics, 5*(2), pp. 110-141.

[49] Madison C., Thompson W., Kersen D., Shirley P. and Smits B., 2001. Use of interreflection and shadow for surface contact. *Perception and Psychophysics* 63, pp. 187-193.

[50] Marcus A., 1992. *Graphic Design for Electronic Document and User Interfaces. Addison Wesley, Reading*.

[51] Marcus A., 1995. Principles of Effective Visual Communication for Graphical User Interface Design. In Baecker, R. M., Grudin, J., Buxton, W.A.S., & Greenberg, S. (Eds.) *Readings in Human-Computer Interaction: Toward the Year 2000*. San Francisco, CA: Morgan Kaufmann, pp. 425-441.

[52] Mayhew D.J., 1992. *Principles and Guidelines in Software User Interface Design.* Englewood Cliffs, NJ: Prentice Hall.

[53] McCormick, P.A., & Klein, R. (1990). The spatial distribution of attention during covert visual orienting. *Acta Psychologica, 75,* 225-242.

[54] Meacham, J.A., and J. Singer (1977). "Incentive Effects in Prospective Remembering." *The Journal of Psychology* 97, 191-197.

[55] Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63,* 81-97

[56] Mills C.B. and Weldon L.J., 1987. Reading text from computer screens. *ACM Computing Surveys*, 19(4), pp. 330-354.

[57] Mullet K. and Sano D., 1995. *Designing visual interfaces: Communication oriented techniques*. Englewood Cliffs, NJ: Prentice Hall.

[58] Murch G.M, 1987. Colour Graphics – Blessing or Ballyhoo? (Excerpt). In Baecker, R. M., Grudin, J., Buxton, W.A.S., & Greenberg, S. (Eds.) *Readings in Human-Computer Interaction: Toward the Year 2000* (pp. 333-341). San Francisco, CA: Morgan Kaufmann.

[59] Murphy, T.D., & Eriksen, C.W. (1987). Temporal changes in the distribution of attention in the visual field in response to precues. *Perception & Psychophysics, 42,* 576-586.

[60] Nagata S., 1993. How to Reinforce Perception of Depth in Single Two-Dimensional Pictures. In Ellis S. (Ed.), *Pictorial Communication in Virtual and Real Environments*, pp. 527-545. London: Taylor and Francis.

[61] Nakayama K. and Silverman G.H., 1986. Serial and parallel processing of visual feature conjunctions. *Nature*, 320, pp. 264-265.

[62] Posner, M.I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3-25.

[63] Posner, M.I., (1990). Structures and functions of selective attention. In T. Boll & B.K. Bryant (Eds.), *Clinical Neuropsychology and Brain Function: Research, Measurement, and Practice* (pp. 173-202). Washington, D.C.: American Psychological Association.

[64] Posner, M.I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. Bouwhuis (Eds.), *Attention and Performance X* (pp. 531-556). Hillsdale, NJ: Erlbaum.

[65] Posner, M.I., Snyder, C.R.R., & Davidson, B.J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General, 109,* 160-174.

[66] Pylyshyn, Z., & Storm, R.W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, *3*, 179-197.

[67] Rushmeier H., Barrett H., Rheingans P., Uselton S. and Watson A., 1997. Perceptual Measures for Effective Visualizations. *IEEE Proceedings of the 8th conference on visualization*, pp. 515-517.

[68] Snowden R.J., 1998. Texture segregation and visual search: a comparison of the effects of random variations along irrelevant dimensions. *Journal of Experimental Psychology: Human perception and performance*, 24(5), pp. 1354-1367.

[69] Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*(11, Whole No. 498). Pp. 1-29.

[70] Tinker M.A., 1963. *Legibility of Print*. Iowa, Ames: Iowa State University Press.

[71] Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97-136.

[72] Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, *95*, 14-48.

[73] Tufte E.R., 1983. *The Visual Display of Quantitative Information.* Cheshire, CT: Graphic Press.

[74] Tufte E.R., 1990. *Envisioning Information.* Cheshire, CT: Graphic Press.

[75] Wallach H. and O'Connell D.N., 1953. The kinetic depth effect. *Journal of Experimental Psychology* 45, pp. 205-217.

[76] Wann J.P., Rushton S.K. and Lee D.N., 1995. Can you control where you are heading when you are looking at where you want to go? In *Studies in Perception and Action III*, ed. B.G. Bardy, R.J. Bootsmal and Y. Guiard, pp. 201-210. Lawrence Erlbaum Associates, Hillsdale, NJ.

[77] Ware C., 2000. Information Visualization: Perception for Design. Morgan Kaufmann Publishers Inc., San Francisco, California.

[78] Wehrend S. and Lewis C., 1990. A problem-oriented classification of visualization techniques, *IEEE Proceedings of the 1st conference on visualization*, San Francisco, CA, USA, pp. 139-143 & 469.

[79] Wheatstone C., 1838. Contributions to the Physiology of Vision: I. On Some Remarkable and Hitherto Unobserved, Phenomena of Binocular Vision. *Philosophical Transactions of the Royal Society, London*, Vol. 128, pp. 371-394.

[80] Wilson H.R. and Bergen J.R., *A four mechanism model for threshold spatial vision*. Vision Research, Vol. 19, pp. 19-32, 1979.

[81] Yeh Y., 1993. Visual and Perceptual Issues in Stereoscopic Colour Displays. In D. McAllister (Ed.), *Stereo Computer Graphics and Other True 3D Technologies*, pp. 50-70. Princeton, New Jersey: Princeton University Press.