WORKING PAPER November 5. 1993

By: Tore Smestad (independent consultant)
Address: Eidsvoldsgt. 13
N-2000 Lillestrøm
NORWAY
Phone: +47 63 81 24 78

Outline for concepts and principles of effective visualization

ABSTRACT

Effective visualization here means to transfer a number of ideas and complex messages in a short time by means of graphics. Thirteen guidelines for such graphics are formulated, partly based on concepts and principles in perception, cognition, and information theory. The guidelines involve visualization concepts and principles that have evolved over many years starting in the area of technical automation. Five examples are judged in this paper according to the presented framework, three from the first book of Edward Tufte. There seem to be good experiences with the guidelines, but rigorous experiments to measure the effectiveness of graphics are not performed. Such experiments might lead to establishment of a theory of effective visualization.

1 INTRODUCTION

Graphics are currently regarded as a powerful communication channel for the transfer of complex messages and understanding. The use of graphics is increasing, especially due to affordable powerful computers, high resolution graphical screens and printers, and associated software. However, there is no established knowledge of how to visualize efficiently (design graphics that make viewers understand a lot in a short time). This paper is a summary of possibly relevant concepts and principles that the author has gradually formulated since 1978. This paper is the result of an engagement by the OECD Halden Reactor Project at Institutt for Energiteknikk in Halden to make a brief summary of today's status. Computer graphics in control rooms is one of their concerns, questions from this area are therefor mentioned.

Efficient use of two mutually supporting documentation forms in a software project in 1978 started the evolution of the current ideas. The needs for understanding and documenting technical issues in programming of technical systems have been an important nutrition since then. This problem may be formulated as a static one: given a complex message, how to diagram the message in order to convey it in a short time. Note that the problem formulation of Man-Machine graphics in control rooms is wider: there is no author with a message, and the understanding (of the current situation) may possibly first be obtained over time and by observing responses to induced control actions. Hopefully, the concepts and guidelines presented here are still useful.

The two books by Edward Tufte: "The Display of Quantitative Information (1) and "Envisioning Information" (2), are probably the best ones written on this subject. The concepts and principles presented in this paper may be seen as other ways of explaining why the good examples in Tufte's books are efficient visualizations. A theory of visualization, if possible to establish, will probably involve the areas of information theory, cognition, and graphical design. This paper may be seen as an attempt of selecting proper parts from these areas in addition to own concepts for such a purpose. Earlier versions of concepts and principles are presented in the references (3) - (7). Some of them are used in a Dr. ing. Thesis (8).

Over the years I have experienced that the presented concepts and principles have inspired the design of more efficient illustrations, both for myself and for other. My hope is that this paper also will do so. In addition, I hope that the paper may bring about a discussion and refinement of the concepts and guidelines, and strengthen the readers general interest for visualization. Hopefully this may lead to the design of experiments that may verify guidelines, thus starting the establishment of a theory of effective visualization.

After this introduction, the paper continues (in section 2) with reviewing concepts and assumptions from perception, cognition and information theory. Then (in section 3) new concepts for classifying and describing graphics are formulated. Concepts from all these areas are then summarized in a vocabulary list. Guidelines for effective visualization are then formulated (in section 4) on the basis of the presented concepts and assumptions. The deductions are somewhat presented and discussed together with a sequence of questions to answer in order to make efficient visualization. A few examples are discussed in the presented framework (in section 5). The establishment of a theory of visualization is briefly commented (in section 6) before the summary and conclusion.

2 TOPICS FROM PERCEPTION, COGNITION, AND INFORMATION THEORY

Viewing and understanding messages represented in graphics involve complex processes of perception and cognition. Concepts and assumptions from these fields are a basis for some of the discussion in section 5, so also with information theory. Key issues from these fields may only be properly treated in textbooks, the presentation here is only a brief review.

A regarded illustration is mapped to the retina where contours, lines, and surfaces probably are identified by a few levels of neurones behind the retina, see (9). Higher level structures of the illustration (e.g. objects, graphs, tables) are identified a bit further down the processing line where these are compared with similar previously stored structures. The brain probably sorts out, relate, and compares structures and "units" on several levels; see (10). We are able to simultaneously treat 3–7 such independent "items" on the conscious level. The viewer may normally decide which set of 3–7 items to focus on. These may vary from covering the whole illustration to just cover a little part of it. The viewer's interest in terms of question(s) and uncertainty may eventually be resolved by one or several comparisons of stored images and previous knowledge. The power of this decoding and interpretation process seems to be more dependent on an enormous "database" of stored images and knowledge than on the processing capacity. The information of the message (see definitions in section 3) is extracted as "differences" between the observed and the expected (or possible) on several levels. In terms of information, the whole process "reduces" the image–information of possibly some tens of millions bits of an illustration to only a few bits of the original question(s) or uncertainty. These concepts and principles are illustrated in figure 2.1.

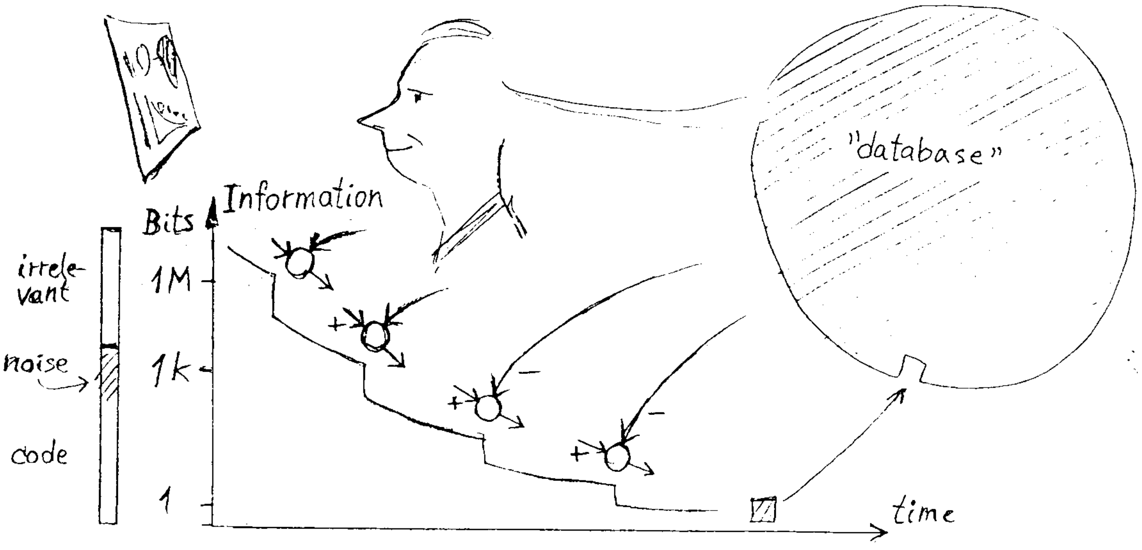


Figure 2.1 The reduction of the image information of an illustration to that of the message

It seems that knowledge of complex issues often means that the occurrences of details (of objects, relations, sequences etc.) are sorted and organized in abstract "scripts". These are much like the class-hierarchy and object-hierarchy used for system analysis according to the objectoriented paradigm, see (11) for the latter. Many feels their knowledge in many cases is represented and organized by a sort of inner view. This may possibly occasionally be represented in a fairly one-to-one fashion by graphics. This inner view may be strongly influenced by observed graphics when acquiring the specific knowledge.

Below are statements summarizing the assumptions and principles mentioned. The term "visual processor" and other terms are defined in section 3.

a) **Our *visual processor* is able to quickly digest high information *images* to *messages* (but not all kinds of high information *images*!).**
b) **Our *visual processor* tries to organize a complex visual *image* into a hierarchy of *visual units* and make relations and comparison between the units.**
c) **Our *visual processor* depends on a huge "database" of visual *images* and knowledge; the information is extracted by series of comparisons (differences) between the observed/ interpreted and the associated expected or possible observations/interpretations.**
d) **Knowledge of complex issues generally involves a linking of the concrete and the abstract; this may take the form of class- and object-hierarchies: the concrete belong to instances of objects, the abstract are general properties of the classes the objects belong to.**
d) **Our knowledge is sometimes represented and organized by an inner view that have features of an *image*.**
e) **The conscious part of the brain is able to focus and manipulate 3-7 *visual units* simultaneously.**

Information theory has a precise definition of "information" relating to coding and transmission of messages; which is probably applicable to graphics. The information of each received "message" (the choice within a set of possibilities) is defined as the logarithm of the inverse of the probability of the message :
logarithm (1 / probability (message)). The unit of this measure of information is "bit" if one uses the logarithm with 2 as the base. One bit of information is accordingly the information of disclosing an uncertainty of 50 percent probability. In computers, one bit means a digit being either a "0" or a "1". This corresponds to the information theory's definition when the coding is done in such an (efficient) way that every digit has an equal probability of 0 or 1. Normally the probability is skewed meaning that each digit carries less than one bit information on an average. The mathematical definition may seem a bit odd. However it may be shown that this is the only formula that satisfies a few axioms, these being intuitively associated with "information". It should be noted that this basic definition of information in a way involves prior knowledge. Getting information means being surprised; the greater the surprise, the more information.

An example of a simple failure situation in a plant can demonstrate the calculation of information. Assume that one knows for sure that one valve among 8 is stuck. Assume that there is no indication nor prior knowledge that points to one valve as more likely to have failed than the other. The identification of the failed valve has accordingly a probability of 1/8. The information content in this message is therefore 3 bits (log2 (1 /(1 / 8))).

Information theory says that messages are transmitted from a sender to a receiver through a communication channel by signals, these being coded representations of the messages. The information content (according to the definition) of the signals has to be at least that of the messages, often it is much higher. This is normally due to inefficient coding, but may be done as a counter-measure against failures in signal transmission. Errors may occur in the channels transmission of signals (noise) and in the decoding process. Signal sensitivity may be defined as the amount of change in the signal when the message is changed. High sensitivity means more reliable message transfer (at the expense of transmission capacity). This because the received (erroneous) signals still will resemblance the signals of the coded message rather than a different message.

The traffic light at a pedestrian walking is an example of a high sensitivity signal. The message (go/walk) has one bit information if the two possibilities have equal probability. The signal has a lot more information being light from either upper or lower light bulb, two colours, and two different images (in Norway it is a person standing or walking). There is a high signal sensitivity since a change in the message changes a lot in the signal. Misinterpreting one of the visual effects (emitting light bulb, colour, and image) does not necessarily means misinterpreting the message (go/walk), thus being a reliable information transmission.

Graphics may be regarded as signals since the graphics is a bearer of the messages to transfer, these being coded in the graphics. These signals have generally high information, here called "image-information", see definitions below. An upper bound of this image-information may be calculated by the number of pixels in the image times the different colours and brightness at each pixels. The information is much less since the probability of the appearance of each pixel is strongly dependent of the neighbours. Even so, the image-information is far greater than the message information. The difference comes from three sources. The greatest contribution normally comes from the low coding efficiency of graphics; low information messages has to be coded with high information visual cues. Note that the message may still be quickly decoded by the brain, low coding efficiency does not imply inefficient visualization. The second source is redundancy. Redundancy is additional coding to make the messages easier to interpret or less likely to be misinterpreted (see the example of pedestrian walking). A third, and possibly large source, is irrelevant coding. This may either be messages of no interest or coding of the message which do not enhance the decoding (understanding). The noise in a signal is generally the amount of unintended changes in the signals. Noise may still have a meaning in graphics even if the graphics does not unintentionally change. The communication channel may be extended to include the process of perception and cognition. Noise may then be defined as the amount of signals that is interpreted other ways than intended or not interpreted at all. The division of the image-information in these four groups are illustrated in figure 2.1.

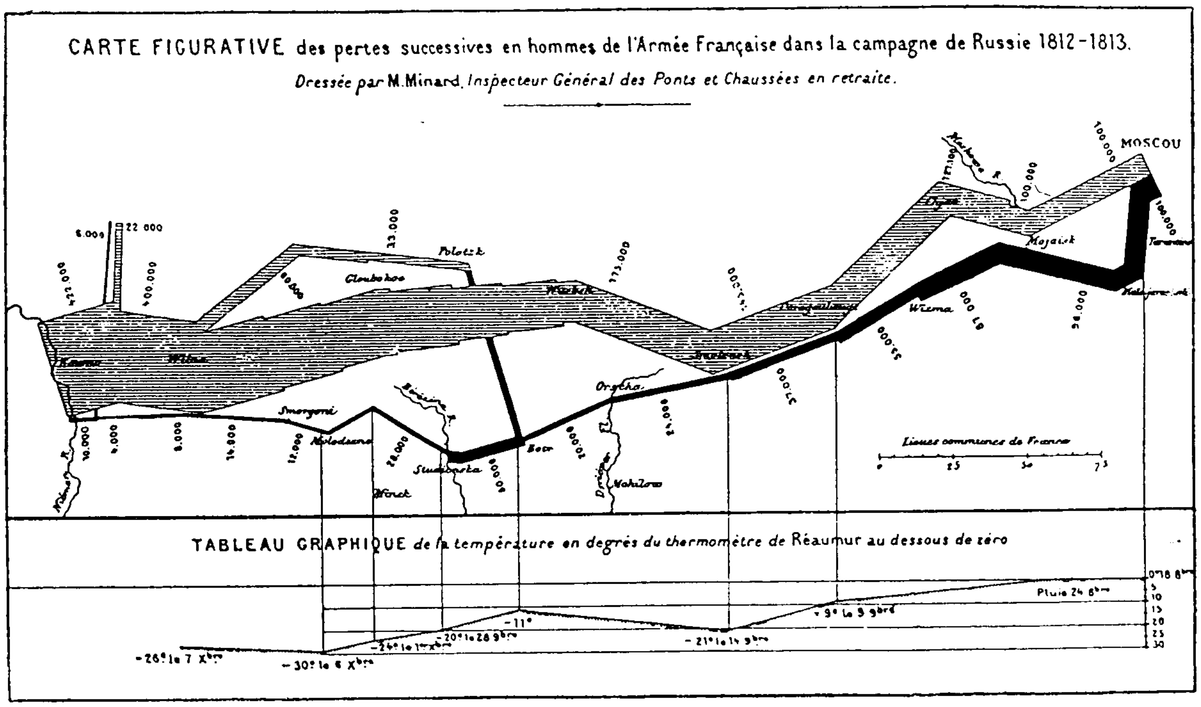
Important statements to summarize points in the text :

f) *Images* may be viewed as *signals* which *transfer messages coded* in them.
g) The *information* of *messages* are normally far less than the *information* of an *image.*
h) The *image-information* may be partitioned in *coding information* and *irrelevant image information*; the latter being *visual effects* that have no *coding* of the *message* or *coding* of irrelevant *message(s)*. The former may involve *redundancy.*
i) *Redundancy* will add to the *signal sensitivity* and increase *message transfer reliability*
j) A low ratio between the *information* of the *message* and the *coding* does not imply *inefficient visualization*

3 SPECIFIC VISUALIZATION CONCEPTS

The following brief description of concepts starts with Minard's illustration (1) of the French army's campaign to Moscow in 1812–1813, see figure 3.1. The visualization concepts are here used as if they already were known; they are described in the end of this section. Important concepts are summarized in figure 3.2 which should be consulted while reading. The numbers in parenthesis in the following section refers to the message groups and the visual effects in figure 3.2.

The Minard's illustration is a good example for this purpose since it uses 5 types of messages, 5 types of visual effects, 4 diagram forms, and the three connection methods. (Some authors regard this illustration as the best ever made!) The French army's march from the river Niemen to Moscow is visualized with a "band-graph" that codes the quantity as the with (in a logarithmic scale), the direction of the march by texture. Message groups in this diagram form: quantity (2), transport (6), situation, mode (7). Visual effects in it: structure without symbols (8), colour/texture (9). The size of the army at specific points are described with numbers. This may be viewed as an expanding connection using text/numbers as a diagram form. Message group in the diagram form: quantity (2); visual effect in it: text/numbers (1). The "band-graph" is transparently connected with a chart showing the main rivers and name of places. Message group in this diagram form: layout/spatial arrangement (8); visual effect in it: picture/appearance (3). The shrinking of the army on the retreat was highly due to the low temperature, which is diagrammed below. Message groups in this diagram form: quantity (2), time information(4); visual effect in it: diagram (6). The temperature diagram is adjacently connected to the (returning) "band-graph" in that the time-axis and the charts east-west axis coincide. Note that this connection enables the identification of the timing of the retreat since the temperature curve is labelled with the time. A summary of the used diagram forms, their seize, messages, visual effects, and connection is found in table 5.1.



Xbre = December 9bre = November 8bre = October

Figure 3.1 Minard's illustration of Napoleons campaign to Moscow 1812–1813

Above, the terms diagram form, message group, visual effect, adjacent–, transparent–, and expanding connection were used. These terms are loosely defined in the end of this section, and they are illustrated in figure 3.2. The specific grouping of "message groups" and "visual effects" in the figure are not essential, other possibilities exist. (These ones may be biased from the area of software and industrial automation where they emerged.) The important point is that an illustration carries messages (that may be grouped) which are to be transferred to the observer by representing them (coding them) by visual effects (that may also be grouped). This division of messages (the information to transfer) and visual representation (the signals) is assumed important.

The three connection methods may be regarded as techniques in placing more information in the same image. Even though these may be seen as layout–techniques, the success of an connection (the ease of understanding the messages from each "component" and their relation) is highly dependent on the viewers interpretation. This means the connections both have a graphical and a semantic aspect. The connection methods should not be regarded as precisely defined, intermediate connections may be found.

In figure 3.2 the ability of a diagram to form connections is depicted as "hooks" on the atoms, which may be viewed as their "valence". The diagrams must have some elements in common in order to be connected. These may be seen as the elements in a n–tupple. The situation of the French army (figure 5.1) at each point in time may, among a lot other variables, be characterised by: geographic position, direction of march, weather condition (temperature, wind, rain/snow), total number of individuals and their grouping (regular soldiers, artillery, cavalry, etc.), equipment, and supply of food. A point (cross–section) of the "band–graph" in a north–west map will represent 3 elements in the n–tupple: position, direction, and (roughly) the number. Other elements of the army's total n–tupple at that moment could be represented by other diagram forms. Only the number is described; this is more accurately represented by digits than by the graph. The (whole of the) "diagram form" of digits represents a single point of the graph, therefore classified as an expanding connection.

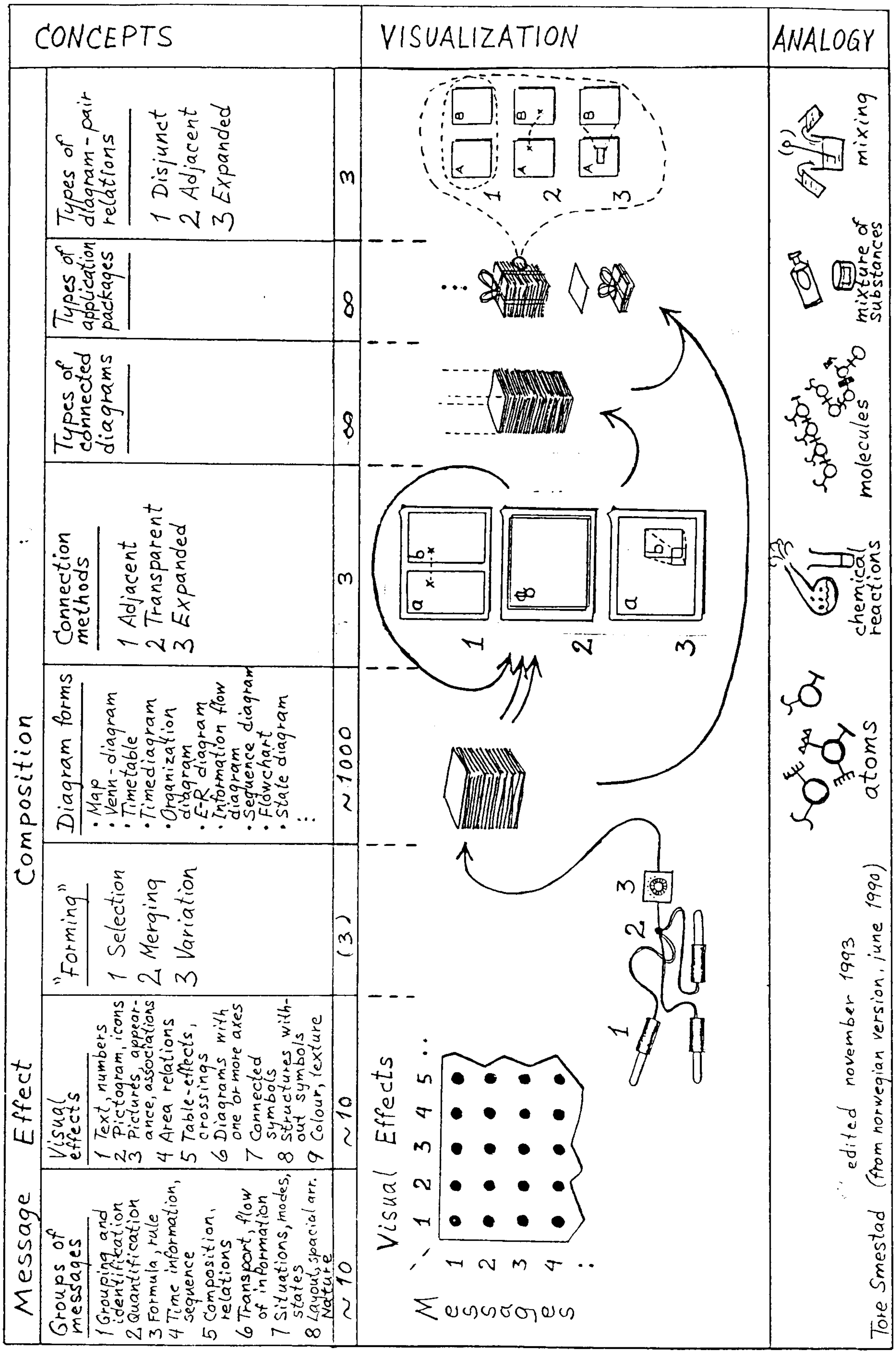


Figure 3.2 A visual summary of some specific visualization concepts

The rest of this section is a kind of glossary of important concepts and terms used in the paper :

coding

representing the *message* by visual means using a *coding scheme* that the viewer understands

c. scheme

a specific way of representing a *message* visually to convey it, c.s. produces the *visual effect*

connected

1) property of an illustration consisting of at least two instances of *diagram forms* being a part of a *connection*

2) property of an instance of a *diagram form* in an illustration being the part of a *connection*

connection

linking between two instances of *diagram forms* by utilizing the representation of one or several common elements or n–tupple(s); there are three types of *connections*: *adjacent c., transparent c.*, and *expanding c.*)

c. method

one of the three following way of linking instances of *diagram forms*

adjacent c.

a c. where the two instances of *diagram forms* occupy different areas of the illustration and one or more elements on one corresponds to one or more elements in the other

transparent c.

a c. where the two instances of *diagram forms* occupy the same area of the illustration and what the positions represent in one instance correspond to what the positions represent in the other

expanding c.

a c. where (the whole of) one instance is related to a single part in the other; the two instances may or may not occupy the same space of the illustration

(Comments to the connection methods described:

an illustration with a single instance of a *diagram form* is of course not *connected*; having two or more instances, the illustration may have one or several *connections*. The *connections* may form a complex structure since a *diagram form* can be *connected* to several other and a single *connection* or a structure of a *connections* may be further *connected* as a unit.)

connection key

independent unit(s) or instance(s) of element(s) in n–tupple(s) being represented in a *diagram form* enabling the *diagram form* to be *connected* to other instances of *diagram forms*

diagram

d. form

a class of diagrams characterized by the types of *message(s)* and *visual effect(s)* used

(Comment to this concept :

according to this definition a table is not a diagram form without stating the *group(s) of message(s)* it represents)

d. instance

one specific item (instance) of a *diagram form* or a structure of *connected diagram forms*

effective visualization

illustrations and graphics resulting in a high *message transfer rate*

image

1) picture in terms of its least graphical elements (i.e. pixels, lines, colours)

2) the spatial area containing the graphical elements (the complete illustration)

mental i.

an inner view representing knowledge having characteristics of an *image*

information

coding i. (in an illustration)

the *image information* of all the *visual effects* representing *messages* or *coding schemes*

image i. (in an illustration)

the *theoretical information* of the *image*

irrelevant (image) i.

the *image information* of *visual effects* irrelevant for interpreting the *messages* or *visual effects* of irrelevant *messages*

message i. (in an illustration)

the *theoretical i.* of the *message*

information (continued)

redundant i. (in an illustration)

the *image information* of *coding* not strictly necessary to convey the *messages*, see *redundancy*

theoretical i. (in an illustration)

the quantity calculated according to the mathematical definition in the theory :

= log2 (1 / probability (subject))

message(s)

the underlying idea(s) or story to convey by the illustration

m. group

messages sorted according to some classification (here a classification of 9 groups is made)

m. transfer

the completion of the reception of the ideas being represented in the graphics

m. transfer rate

the amount of *messages transferred* pr unit of time

m. transfer reliability

the probability that the intended *message* is received correctly

noise (of an illustration)

1) (an instance) *visual coding* that are misinterpreted or has delayed the interpretation

2) (characterization) *visual coding* that are likely to be misinterpreted or delay the interpretation

redundancy (in an image)

part of the *image* that are not strictly necessary for interpreting the message, consists of additional *coding* by use of more than one *coding scheme* or clarifying of *coding schemes*

signal

carrier of the *messages* through a communication channel, here: an *image* that contains *message(s)*

s. sensitivity (of a diagram form)

the amount of perceived change in the *image* as a result of a change in the *message*

valence

(here) a property of a *diagram form* or illustration: the ability to make *connections* to other *diagram forms* by the representation of identifiable elements or n–tupple(s); corresponds to the number of *connection keys*

visual–

v. processor

a term used for the joint calculating features of the eye and brain making it possible to digest the *image* projected on the retina to meaningful *messages* (the visual processor cannot do its job without an enormous database of stored *images* and knowledge)

v. cue

features of the *image* that may carry or help decoding a *message*, may be equivalent to *v. effect*

v. effect

feature of the *image* that may carry some *message*; here these are sorted into 8 groups

v. structure

the structure of relations between the *visual units* and associated *connection keys* in an *image* as intended by the designer

v. unit

the whole or a portion of an *image* that is treated as a unit in some respect; examples are *images* representing a physical object, a graph, a variable or a group of such "units".

4 DEDUCIBLE GUIDELINES FOR EFFECTIVE VISUALIZATION ?

This section states guidelines and presents deduction relations from assumptions and principles stated earlier. Guidelines are tried formulated for experimental support. A guideline is here assumed supported if experiments show a positive correlation between its degree of being met and the message transfer capacity. The terms "degree of being met" and "transfer capacity" have to be quantified in order to do such experiments. This topic is beyond the scope of this paper. There are several important questions not explicitly treated in the presented guidelines. Some are mentioned in the discussion at the end of this section as warnings and as inspirations to further thought.

Below is presented 13 guidelines for effective visualization. There will of course be a lot of other guidelines aiming at other levels of detail and using other terms. One example is: "an image should be comfortable to look at having proper contrast, adequate resolution, soft colours, and having well balanced spaces". Such guidelines are seen as supplementary to the ones here.

1) Place a lot of *messages* into single *images*.
2) Make illustrations with high *image–information* and a low ratio between the *irrelevant image information* and that of the *coding–information*.
3) Partition an *image* into gradually smaller parts.
4) Arrange the *visual structure* so that 3–7 *visual units* may be naturally focused at a time.
5) Select *diagram forms* with a high *signal sensitivity* of the *message(s)* to transmit over the actual range of *message(s)*
6) Use obvious *coding schemes*; don't change them, clarify them explicitly if not obvious.
7) Select *diagram forms* and *coding* that are likely to resemblance humans *mental image*.
8) Make illustrations with a *visual structure* and content according to prior knowledge.
9) Use several *diagram forms* in the same *image*.
10) Select *diagram forms* representing different levels of abstraction in the same *image*.
11) Pair many instances of n–tupple elements of the selected *diagram instances* by the *connection methods*.
12) Use *transparent* and *adjacent connection* to minimize the position–uncertainty of *visual units*.
13) If the illustration does not contain all messages, select *diagram forms* with *connection keys* to (potentially) supplementary illustrations (that is: furnish *valence* to the illustrations)

Guideline 1) is motivated by the very definition of efficient visualization and assumption a). The last part of guideline 2) is obvious since irrelevant coding or messages will slow the interpretation process. High image–information then means high coding information, giving room for effective coding schemes. Note that there is no claim that a low ratio between the image's coding– and the image's message–information will increase the efficiency (the ratio will always be much greater than one). The image–information of an icon is normally much higher than that of the corresponding function name, but we understand it quicker.

Guideline 3) is a simple way of obtaining 4). Guideline 4) is motivated by assumption b) and e). Guideline 5) is an other way of stating one should select a diagram form that clearly shows the message and discriminates between variations of it. Guideline 6) is obvious; if the coding scheme is not obvious, it will take longer time to understand the image if possible at all. A change normally confuses and may lead to misinterpretation.

Guideline 7) and 8) is motivated by assumption c) and that information means surprise. It seems reasonably that the message transfer rate is increased if the comparisons are based on a well known base, see figure 2.1. Guideline 9) is especially aimed at complex messages with several aspects. Then a single diagram form is unlikely to satisfy guideline 5), therefore several diagram forms. Several diagram forms may also contribute to the guidelines 1), 2), and 4).

Guideline 10) is motivated by assumption d). Guideline 11) asks for a sort of visual network of the n–tupples of the message. Making the relations between the n–tupples more apparent will add to the information and coding of the image, thus contributing to guidelines 1) and 2). Guideline 12) is obvious since position uncertainty means time to find the elements and make the comparison between them more difficult and time consuming. Guideline 12) means to enable the use of guideline 11) on separate images.

Important questions and possibly objections could be worthwhile to discuss here. Only a few topics is treated below.

Guidelines 1) and 2) states the images should be of high information density. Generally, there will be a trade–off between the information content of each image and the number of images. The information density where one is better off splitting the messages on several images, are probably much higher than one believes.
The observation time is not explicitly treated. The message transfer rate of a given image will generally be highly dependent on the observation time. The guidelines are formulated under the assumption of a long observation time. This distinction is believed to be important, but is not treated here.

Also, the guidelines are formulated for a static situation: given a message, how to effectively transfer it. This is valid in software documentation, textbooks and user manuals. It is not the case in a control room situation. In a dynamic situation, there is not a static message to transfer. It is more like walking in the dark with a searchlight: which spots to enlighten to verify a safe march ? Such a feedback situation will probably influence the set of proper guidelines.

Note that the guidelines generally require knowledge of the observer and the situation (especially no 6, 7, and 8). This means the term "effective visualization" is no characterization of the illustrations in their own right. If "effective visualization" is only concerned with a high message transfer rate, what if the messages are ill-structured and else unsuited for enlightening the problem domain ? (This is claimed to be the case in software engineering before the objectoriented methodology was available.) Tufte (1) addresses this question; he states that "graphical excellence" is ..."the well-designed presentation of interesting data - a mater of substance, of statistics, and of design". The guidelines do not address this point, with a possible exception of no 7), 8), and 10). Prior knowledge and inner representations are believed to be object-oriented and having different levels of abstraction, which is here assumed to be beneficial.

Discrimination and treatment of the concepts of "coding", "noise" and "irrelevant messages" are not properly done. What Tufte (1) terms "distortion" is a special case of "noise". To avoid distortion he claims that "The number of information-carrying (variable) dimensions depicted should not exceed the number of dimensions in the data". Irrelevant messages may also be "noise" as defined here, since they may slow the interpretation. However, the distinction is subtle. In a large map, there is a lot of irrelevant messages for a specific journey, but this does not generally slow down the interpretation of the interesting messages.

Maybe the concept of ergonomics also should play a part. There should be little extra mental effort in understanding graphics, meaning if one gets mentally tired, this ought to come from the mental effort of acquiring the new knowledge at the message-level, not the visual decoding of the graphics. This question may be somewhat addressed in the guidelines 7) and 8), but there may be more to this question.

The production of efficient visualization will involve a price aspect. Efficient computers, displays, and graphical software are still expensive. It is time-consuming to design and draw illustrations with a high information density, thus costly. The benefit of efficient visualization will have to be weighted against this cost in a practical situation.

To summary this section, let us review what is necessary to achieve effective visualization according to the stated guidelines (note that all of the points have not been explicitly addressed in the paper) :

1) Who is to interpret the graphics, what are the questions they have, what do they have of prior knowledge, and what are their internal representations ?
2) What are the messages desirable to transmit, which sets of n-tupples are involved ?
3) Which diagram forms have the highest signal sensitivity over the range of messages, and do they represent the actual n-tupples suitable for connection ?
4) Which set of diagram forms may be connected to constitute an effective single image ?
5) How to partition the messages into different images to an efficient "package" of images ?

5 ANALYSIS AND DISCUSSION OF A FEW EXAMPLES

This section briefly applies the concepts and principles on the diagrams in this paper as examples, two additional illustrations from Tufte's first book (1) are included here. The visual structure of the examples are summarized in table 5.1. Table 5.2 summarizes how the examples are judged according to the guidelines.

Figure 2.1 is viewed as an adjacent connection of the drawing of a viewer of a diagram and the diagram of the information reduction. The former has m.g. (message groups) : transport (6) and "nature" (8), and v.e. (visual effects) : appearance (3). The latter having m.g. (6) and time (4), and v.e. diagram (6). Distance and time are the connection keys. The diagram of the viewer is expanded by a diagram illustration the vast database of the brain, m.g.: quantification (a coarse one!) (2), v.e.: area relation (4). The diagram of the information reduction is expanded by small diagrams at some points where the retina/brain (the visual computer) is assumed to perform a "subtraction", m.g. formula (3), flow of information (6), v.e.: connected symbols (7). These are also adjacent to the "database". The leftmost part of the diagram is expanded by a column indicating the grouping of information in the regarded image, m.g.: grouping and identification (1), v.e.: area relation (4).

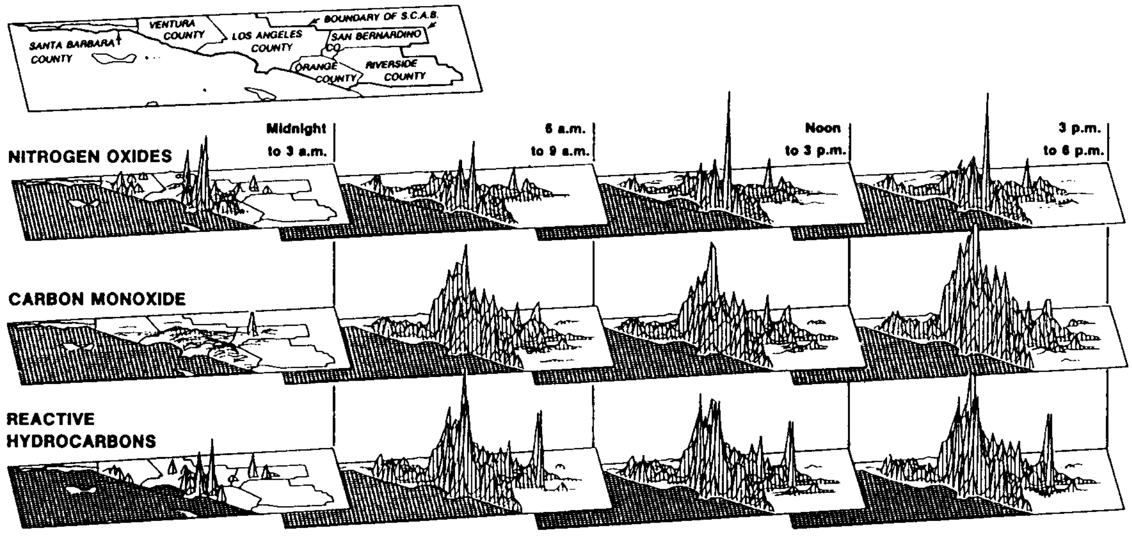


Figure 5.1 Illustration of measured pollution in the Los Angeles area

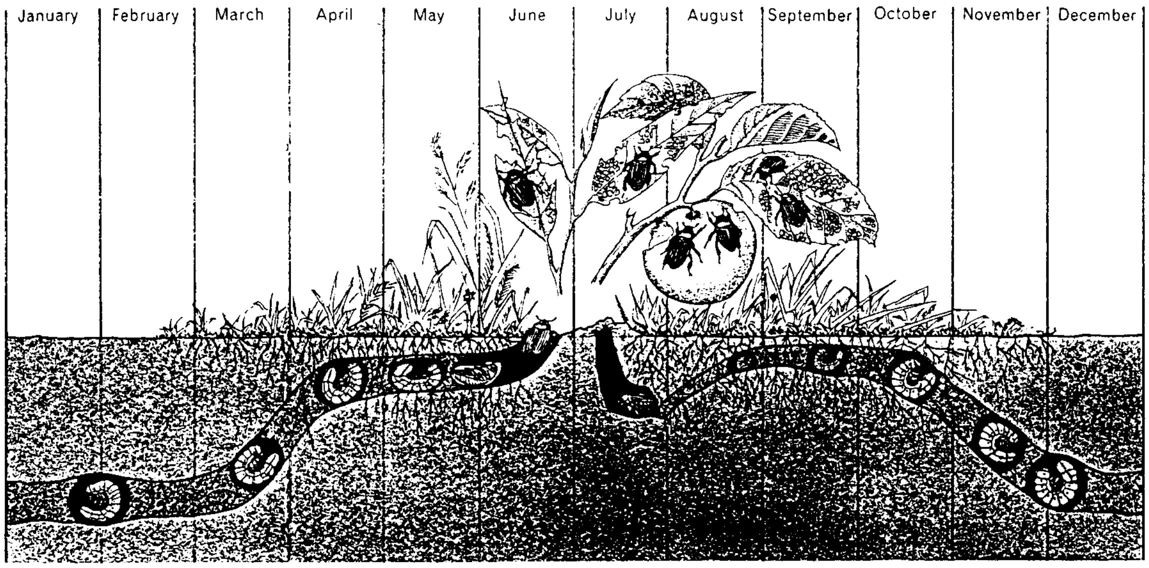


Figure 5.2 Illustration of the life cycle of the Japanese beetle

Figure 3.1 is already described in section 3. Figure 3.2 might be seen as a table, m.g.: grouping and identification (1), v.e.: table (5). The columns are eight concepts (group of messages, visual effects, ..), the rows are labelled "concepts", "visualization", and "analogy". The columns of the upper row are expanded by textual descriptions, m.g.: grouping and identification (1), v.e.: text (1). The second row is expanded by a flow diagram, m.g.: flow (6), v.e.: connected symbols (7). The "items" of the flow diagram (the concepts) are expanded by diagrams that associates with them, m.g.: identification (1), v.e.: appearance (3). Note that the columns are not explicitly drawn in this second row, neither in the third showing the analogies from chemistry.

Figure 5.1 consists of 12 items of 3–axes diagrams, m.g. quantification (2), v.e.: diagrams (6). However, one may say that the illustration is mainly one big table or rather a diagram with axes time of the day and air pollutants, m.g.: grouping and identification (1) and time (4), v.e.: crossings (5). This big "diagram" serves to uniquely position the 12 small diagrams, which are expansions of the former. The connection keys are here time of day and air pollutant. Adjacently connected to the diagrams is a map over the area, which serves to ease the interpretation of the diagram.

Figure 5.2 has an transparent connection of a sort of natural picture and a partly invisible diagram. The latter shows the height/depth of the insects location as a function of the time of year, m.g. quantification (2) and time (4), v.e.: diagram (6). The former happens to show the same message (2) due to the same spatial arrangements, but it also shows the appearance of the insect and its surroundings, m.g. layout, nature (8), v.e. picture (3). A picture of the plant at the time of the breeding is expanded, m.g. nature (8), v.e. picture (3).

Diagram form	Area	#	M.g.	V.e.	ADJ.	TRA.	EXP.
Figure 2.1 :							
Person viewing an illustration	30%	1	6, 8	3	*		*
Illustration of size of the brains "database"	20%	1	2	4	| *		*
Diagram of reduction of the information	40%	1	2, 4, 6	6	* |		* *
Illustration of the many comparisons	3%	4	3, 6	7	*		* |
Bar with groups of information	2%	1	1	4			*
Figure 3.1 :							
Chart of part of Europe	40%	1	8	3		*	
"Band graph" with texture	50%	1	2,6,7	8,9	*	*	*
Numbers	1/5%	25	2	1	|		*
Temperature diagram	30%	1	2,4	6	*		
Figure 3.2 :							
Table	100%	1	1	5			* * *
Texts	30%	8	1	1	*		* | |
"Flow" from messages to illustrations	25%	1	6	7	|		* * |
Illustrations of elements in the "flow"	15%	10	1	3	*		* |
Illustrations of analogies	5%	5	1	3	*		*
Figure 5.1 :							
"Diagram" of air pollutants and time	85%	1	1,4	5			*
Diagram of concentrations at places	7%	12	2	6	*—*		*
Chart over the Los Angeles area	15%	1	8	3	*		
Figure 5.2 :							
Diagram of height/depth over the year	100%	1	2,4	6		*	*
Drawing of the insect in nature	100%	1	2,8	3		*	|
Drawing of blades at breeding time	15%	1	8	3			*

Table 5.1 Diagram forms and connection structure of the examples

Area : % of the image area "covered"
\# : instances of the diagram form
M.g. / V.e. : message group / visual effect

ADJ. : Adjacent connection
TRA. : Transparent connection
EXP. : Expanding connection

GUIDELINES	THE EXAMPLES (FIGURES)				
	2.1	**3.1**	**3.2**	**5.1**	**5.2**
1) Place a lot of messages into single images.	1	2	2	3	2
2) Make illustrations with high image-information ...	1	2	2	3	3
3) Partition an image into gradually smaller parts.	1	2	3	2	0
4) Arrange the visual structure so that 3-7 visual ..	1	3	3	3	1
5) Select diagram forms with a high signal sensitivity of ...	1	3	2	2	3
6) Use obvious coding schemes; don't ch., clarify if ...	2	3	1	3	3
7) Select diagram f. and coding that are likely to ress...	2	3	1	2	3
8) Make illustrations ... according to prior knowledge	1	2	1	2	2
9) Use several diagram forms in the same image.	1	3	3	1	2
10) Select ... representing different levels of abstraction ...	3	2	2	1	2
11) Pair ... n-tupple elements ... by the conn. methods.	1	2	3	3	3
12) Use transp. and adj. conn. to min. pos.-uncertainty ...	-	-	-	3	-
13) If ... not contain ... diagram f. with connection keys.	-	-	-	-	-

Table 5.2 Judgement of the guidelines' "degree of being met" in the presented examples

"Scores" of "degree of being met" :
- : irrelevant guideline
0 : negligible
1 : to some extent
2 : moderate
3 : very well

6 STEPS IN ESTABLISHING A THEORY OF EFFECTIVE VISUALIZATION

An established theory generally has to contain the following elements :

1) a set of fairly well-defined and self-consistent concepts that describes phenomena of an area
2) a set of statements (theorems) that may be subject to experiments
3) a set of experiments that have the power of falsifying statements in 2, but have not yet done so

There has to be a fairly common interpretation and agreement of the concepts in 1). An overlap with established theories is regarded as a strength. This means that some of the concepts and statements from established areas may be used and have relevance in the new area, and vice versa. The interpretations of the experiments in 3) have to survive open criticism.

This paper has touched the points 1) and 2); the guidelines are regarded as statements under 2). The acceptance of the visualization concepts is not established, but it seems that people tend to classify illustrations the same way using the concepts (classifications like those shown in table 5.1). In addition, there seem to be relevant relations to perception, cognition, and information theory. Own experience and other's seem to agree with the guidelines, and the good and bad examples in Tufte's books (1) and (2) also seem to agree with them.

However, no rigorous experiments are done. A next step of establishing a theory of effective visualization, if possible to establish, is to perform experiments that can test some of the guidelines.

7 SUMMARY AND CONCLUSION

This paper has presented thirteen guidelines for effective visualization (section 3). These are partly based on concepts and principles from perception, cognition, and information theory, which are stated in summary form (section 2). The guidelines are to a large extent formulated with new concepts of visualization, these and other concepts are summarized in a vocabulary list (section 3). The relations between the basic assumptions and the guidelines are sketched together with a brief discussion of some important questions.

This edition of the paper is the result of an engagement by the OECD Halden Reactor Project at Institutt for Energiteknikk in Halden. The hope is that these guidelines may inspire the design of new and more suitable control room graphics for Man-Machine Interfaces. The basic questions of this area is wider than those which motivated the development of these ideas, as mentioned in section 1 and 3.

Even if there are indications that these concepts may be generally accepted and that the guidelines result in effective visualization, the way to an established theory of effective visualization may be considerably, if reachable. Experiments that can test some of the guidelines seem to be an important step toward such a theory.

REFERENCES

(1) Edward Tufte (1983) : "The Visual Display of Quantitative Information", Graphics Press, Cheshire, Connecticut

(2) Edward Tufte (1991) : "Envisioning Information", Graphics Press, Cheshire, Connecticut

(3) Tore Smestad (1983) : "The missing link: Funksjonsspesifikasjon og -beskrivelse av automatiserings-systemer", Automatisering nr 8 1983

(4) Tore Smestad, Ole Kristian Andersen (1988) : "Integrated projection illustrating", ACM Software Engineering Notes, Jan. 1988

(5) Tore Smestad (1989) : "Store muligheter med manipulering av figurer", Teknisk Ukeblad, nr 35 1989

(6) Tore Smestad (1989) : "Programmering av industrielle styresystemer, Mot effektive beskrivelser", Automatisering, nr 9 1989

(7) Tore Smestad (1990) : "Can a new set of visualization related concepts be used to guide the design of man-machine graphics?", Institutt for Energiteknikk, Halden, Febr. 1990 (not published)

(8) Ommund Øgård (1990) : "A situation adaptive presentation system for process control", Dr. ing. Thesis, Norwegian Institute of Technology, Trondheim, Okt. 1990

(9) Jules Davidoff and David Concar (1993) : "Brain cells made for seeing", New Scientist, 10. April 1993

(10) James S. Albus (1991) : "Outline for a theory of Intelligence", IEEE Transactions on Systems, Man, and Cybernetics, No 3 May/June 1991

(11) Ivar Jacobson (1992) : "Object-Oriented Software Engineering, A Use Case Driven Approach", ACM Press, Addison-Wesley, 1992