To Picture or Not to Picture: How to Decide

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Graphics can be startlingly effective, as Bertin,[1] Cox,[2], and Tufte[3] have illustrated. They can also be costly failures. One good example of graphic design failure is the development of the signage for the Washington, DC subway system.[4] The signs for the stops were arranged vertically letter-by-letter on the subway platforms. The readers were unable to read them in the brief time the subway's speed allowed. The malfunctioning signage system had to be redesigned at an additional cost of nearly one million dollars. The costs from ineffective use of graphics in education may be harder to calculate, but they are undoubtedly substantial. On the one hand, the failure to use graphics, when they are the best – or even the only – way to communicate results in many lost opportunities to educate. On the other hand, the use of visuals in circumstances in which they are ineffective or even interfere with learning, may result in persistent misconceptions that hinder future learning.

Obviously, both designers and their audiences would prefer effective graphics. Why are so many visual representations ineffective or worse? The answer proposed in this paper is that the process of conceptualizing and creating visual representations rarely is grounded in knowledge that goes beyond the intuitions of the designer. To create effective graphics, one needs to understand how the audience (users) of the product understand cognitive material and how they will use the product. This knowledge can be gathered only by direct research that tests the effectiveness of the material with the appropriate audience. Thus, this paper has three central arguments:

1 Intuitions of the designer are not sufficient to understand how users will process and learn from graphics. All humans, no matter how bright, creative and experienced, suffer from certain habits of reasoning that distort their ability to intuit how users will understand and respond to graphics. Some of the large body of research documenting these reasoning tendencies will be described.

2 To develop general principles that can guide a more effective design process, it is necessary to conduct scientific research on how people understand and learn from graphics. Examples of research on the effectiveness of using visual diagrams and pictures to supplement educational texts will be reviewed. Although, as is typical of research with

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30 million years and counting

After the photon has made
three-fourths of its journey,
it gets to about the same range as M-82,
a galaxy near the Big Dipper
which I find fascinating
because we know
there is an incredible explosion
in progress here
and we can watch it
in the most exquisite slow motion.
In reality,
the explosion is rushing through the galaxy
at the speed of light,
but at this great distance
even that seems slow.
Meanwhile,
on our own little planet,
things are taking shape
as we now know them.
Grass has appeared.
The atmosphere has assumed
its modern composition.
Grazing animals are common.
But we are still several million years
from the point where apemen
diverge from the Chimpanzee family
and begin to walk upright.

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5
Tufte, E.R. 1983. *The Visual Display of Quantitative Information.* Cheshire, Connecticut: Graphics Press.

6
Winn, W.D. 1987. Charts, graphs and diagrams in educational material. In D.M. Willows and H.A. Houghton, eds, *The Psychology of Illustration* (volume 1 Basic Research). New York: Springer-Verlag, 152-198.

7
Neurath, M. 1974. Isotype. *Instructional Science,* 3, 127-150.

8
Macdonald-Ross, M. 1977a. How numbers are shown: A review of research on the presentation of quantitative data in texts. *AV Communication Review,* 25, 359-410.

9
Schutz, H.G. 1961. An evaluation of methods for presentation of graphic multiple trends. *Human Factors,* 3, 108-119.

10
Cuff, D.J. 1973. Colour on temperature maps. *The Cartographic Journal,* 10, 17-21.

11
Szlichcinski, K.P. 1980. The syntax of pictorial instructions. In P.A. Kolers, M.E. Wrolstad and N. Bouma, eds. *Processing of Visible Language* (volume 2). New York: Plenum, 113-124.

humans, there are more questions than answers in this research, the body of literature does yield a few principles that are adequately established to be applied to the design process. The research also suggests promising leads for the future.

3 The situations in which designers must design are far more disparate than the principles currently established. When scientific research fails to help, designers need not rely entirely on intuition. Rather, they can apply the user-based prototyping model of design development that has been applied successfully in computer software design. The nature and requirements of this process will be described.

What is wrong with the intuitive approach?

Today much design is based on intuitive skills developed by immersing oneself in the practice of design. In one sense this obviously works – one develops a grab bag of techniques and intuitively picks the one that seems best for the occasion. Some practitioners take it one step further and develop sets of principles based on their personal experience or on exploring the extant literature of others' work. This permits them to influence other practitioners and to teach student designers.

If the intuitions of experienced designers were sufficient to produce designs that communicate effectively, the history of various design fields would not be littered with sad tales of failed designs. In addition, intuitions often clash. For example, Tufte[5] argues that effective statistical graphs should present many numbers in a small space and argues that small data sets are better represented by tables. Yet Winn[6] and predecessors such as Neurath[7] and Macdonald-Ross[8] consider Neurath's isotype chart very effective and isotype charts typically chart only a few pieces of data (much as the bar graph). Schutz[9] found that single graphs with multiple lines led to fewer errors than the small multiple graphs recommended by Tufte. Whom should we believe?

Some design mistakes may be the result of designers being so focused on aesthetic issues that they don't pay adequate attention to issues of effective communication. Even if this is true, simply convincing designers that effective communication should be central in their design considerations is not sufficient to ensure that the resulting designs will be informationally effective. Why, then, are there still so many ineffective designs?

The answer, I believe, is that designers typically rely on only two sources of information. First, they attend to their own reactions and assume that the audience will have similar reactions – we're all human, right? Wrong. It is quite clear that the differences among humans, even in their reactions to graphics, is immense and it is impossible to generalize accurately from one's own reactions, no matter how typical one considers oneself. This was demonstrated by Cuff[10] with maps and Szlichcinski[11] with visual instructions. In addition, designers are experts in interpreting graphics, so their reactions are likely to be quite differ-

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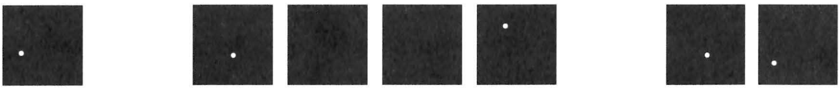

37.8 million years

At 2.2 million years away,
it is inside the "local" group of galaxies
to which our own Milky Way belongs.
The great M-31,
one of the largest galaxies known,
is in this region.
Visible to the naked eye
as a hazy patch on a clear summer evening,
M-31 contains more than
300 billion individual stars.
Spread over 180,000 light years,
this vast star system
is about twice the size of our own galaxy.

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12
Hartley, J. 1982. Designing Instructional Text. In D. Jonassen, ed. *The Technology of Text* (volume 1). Englewood Cliffs, New Jersey: Educational Technology Publications, 193-213.

13
Gauron, E.F. and Dickinson, J.K. 1969. The influence of seeing the patient first on diagnostic decision-making in psychiatry. *American Journal of Psychiatry*, 126, 199-205. See also Sandifer, M.G., A. Hordern and L.M. Green. 1970. The psychiatric interview: The impact of the first three minutes. *American Journal of Psychiatry*, 126, 968-973.

14
Taylor, S.E. and S.C. Thompson. 1982. Stalking the elusive "vividness" effect. *Psychological Review*, 89, 155-181.

15
Anderson, C.H. 1983. Abstract and concrete data in the perseverance of social theories: When weak data lead to unshakable beliefs. *Journal of Experimental Social Psychology*, 19, 93-108.

ent from those of the naive consumers of their graphics. Furthermore, as Hartley[12] pointed out, it is easy to assume that because you have done something, it must be an improvement over earlier versions, whereas in actuality the change may not be for the better.

The second source of information is informal observation of the reactions of others to graphics. This approach is also doomed to failure. Humans are wonderfully creative, intuitively perceptive, and naturally theoretical, but we are by our very nature egocentric, biased and overconfident when we have to form opinions based on our impressions of others' behaviors. The next section describes some of the research that has demonstrated how humans misjudge the kinds of information that they need to assess whether designs communicate to their audience. Although this research has not been done in the context of designers designing, studies have been done in a variety of situations, which makes them likely to be generally applicable. Thus, the goal of this section is to demonstrate that people can not trust their informal impressions.

Initial opinions are formed rapidly and are based on inadequate evidence

The starting point in forming impressions of the reactions of others is the initial hypothesis. In visual communication it is the initial assessment of the needs and capabilities of the audience and/or the initial impression of the effectiveness of a particular representation (e.g., the designer's decision to make the DC subway stop signs read vertically). In clinical psychology and psychiatry this initial hypothesis is the diagnosis of the client. Social psychologists often study the formation of people's first impressions of others. In science it is formulating the initial belief about causal relations. Both experts and novices form opinions quickly and on the basis of remarkably little and weak evidence. For example, mental health professionals form their initial diagnostic impressions within the first five minutes of contact with the patient.[13]

The bases on which people form their initial impressions is consistent with the speed of their formation. They rely on snippets of knowledge that "stick in their minds" rather than systematically considering alternative hypotheses and the widest range of data that might differentially support these alternative hypotheses, a more time-consuming but less error ridden process. To make matters worse, these snippets are often inadequate or misleading. Some of the important types of information that attract people's attention follow.

Knowledge of individual cases

When people know (or know about) one or two people who epitomize a particular belief, they will consider that belief supported without even asking whether those cases are typical or atypical (cf. review by Taylor and Thompson[14]). Anderson's study[15] is a particularly nice

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38.2 million

And as the photon leaves
the Andromeda galaxy behind,
interesting things
are starting to happen on earth.
Interesting, at least,
from our parochial perspective,
for when the photon
is a mere 1.8 million light years away,
Homo erectus, the first true man,
arises in China.
Homo sapiens –
the wise guy –
has to wait another million years.

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16
Manstead, A.S.R., C. Proffitt and J.L. Smart. 1983. Predicting and understanding mothers' infant-feeding intentions and behavior: Testing the theory of reasoned action. *Journal of Personality and Social Psychology*, 44, 657-671.

17
Smith, R.E. and W.R. Swinyard. 1983. Attitude-behavior consistency: The impact of product trial versus advertising. *Journal of Marketing Research*, 20, 257-267. For additional examples, see Fazio, R.H. and M.P. Zanna. 1981. Direct experience and attitude-behavior consistency. In L. Berkowitz, ed. *Advances in Experimental Social Psychology* (volume 14). New York: Academic Press, 161-202.

18
Temerlin, M.K. 1968. Suggestion effects in psychiatric diagnosis. *Journal of Nervous and Mental Disease*, 147, 349-353.
Langer, E.J. and R.P. Abelson. 1974. A patient by any other name . . . : Clinician group difference in labeling bias. *Journal of Consulting and Clinical Psychology*, 442, 4-9.

example of this phenomenon. One group of undergraduates read two case studies exemplifying the hypothesis that good firefighters are high risk-takers. In one case the firefighter was good at his job and was also a high risk-taker, and in the other case, the firefighter was poor at his job and was a low risk-taker. Another group of undergraduates were given comparable case studies exemplifying the opposite relation (good firefighters are low risk-takers). Most subjects had no difficulty forming a causal hypothesis on the basis of the two case studies. The subjects were then informed that the case studies were fictitious and subsequently asked about their true beliefs about the relationship. The subjects acted as if the causal relationship they had been exposed to was true – they used it to make predictions about five additional case studies, for example – and they still held that belief a week later.

Personal experiences

One's own personal experiences are perhaps a specific type of case study. At least some studies have found the same strong influence of personal experience that has been found for case studies. For example, women who have nursed a previous baby respond more strongly and consistently to the prospect of nursing a new baby than do women who have not yet nursed a baby.[16] People who taste a new product are more likely than people who have simply read an ad to commit to buying the product.[17] It is not clear that direct experience has a particular impact beyond that provided by a case study of another (cf. Taylor and Thompson[14]), but it is important to note that one's own experience can have at least a comparable effect. For example, designers who have received rave reviews from one design may easily become convinced that this type of design is generally effective and superior to another of their designs that did not receive such rave reviews. Of course, those two experiences may be just as fortuitous as the firefighter case studies in the Anderson study. Likewise, writers on design principles, such as Bertin and Tufte, illustrate their points with particularly nice examples of particular kinds of designs – case studies – but they do not provide any evidence that principles so derived are what differentiates effective from ineffective graphics.

The influence of expert opinion

The influence of an expert or authority has been documented in a variety of settings. For example, Temerlin[18] found that psychiatrists, psychologists and graduate students in clinical psychology were likely to diagnose a patient (who actually was normal) as psychotic if they were told that a high-prestige colleague believed the patient was psychotic even though he looked neurotic (by 60, 28, and 11 percent, respectively). None of the experts without access to this biasing information diagnosed him as psychotic (cf. also Langer and Abelson, 1974).[18] In the world of design, certainly the design principles developed by experts would be expected to serve a similar role in forming impressions of goodness of designs.

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39.5 million

Now our photon
is really getting near.
There is a dwarf galaxy in Ursa Minor
near the Little Dipper
that's about half a million light years from us.
That's how far out our photon is
when Homo sapiens first puts in an appearance.
Thirty-nine and a half million years
of a 40-million-year journey is behind it
before modern man even emerges from the mist.
It will cut the distance in half again
before this wise animal learns
to control the use of fire.

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19
Lichtenstein, S., P. Slovic, B. Fischhoff, M. Layman and B. Combs. 1978. Judged frequency of lethal events. *Journal of Experimental Psychology: Human Learning and Memory*, 4, 551-578.

20
Higgins, E.T. and G. King. 1981. Accessibility of social constructs: Information processing consequences of individual and contextual variability. In N. Cantor and J.F. Kihlstrom, eds. *Personality, Cognition and Social Interaction.* Hillsdale, New Jersey: Erlbaum, 69-121.

21
Wason, P.C. 1960. On the failure to eliminate hypotheses in a conceptual task. *Quarterly Journal of Experimental Psychology*, 12, 129-140.
Wason, P.C. and P.N. Johnson-Laird. 1972. *Psychology of Reasoning: Structure and Content.* Cambridge, Massachusetts: Harvard University Press, 204-214.

22
Mahoney, M.J.. and B.G. DeMonbreun. 1977. Psychology of the scientist: An analysis of problem-solving bias. *Cognitive Therapy and Research*, 1, 229-238.

Availability (accessibility)

Another influence is that of availability (or accessibility). This describes people's tendency to form impressions or hypotheses based on what is easily accessible to their memory rather than on the basis of consideration of all the information. For example, when people are asked to estimate the probability of dying from various causes, they overestimate the probability of dying from causes with which they are familiar.[19] For example, people overestimate the frequency of deaths from causes typically reported in newspapers, which tend to be relatively rare but spectacular forms of deaths. Newspapers report homicides nine times more frequently than they report suicides and spend fifteen times the space even though suicides are twenty-three percent more frequent.

Differential familiarity is not the only basis for accessibility – expectations, motivation, recency of activation, frequency of activation, salience (prominence and/or distinctiveness), and relation to other accessible constructs also make information more or less accessible.[20] It is clear that we will use whatever constructs happen to be available to us at the time, whether or not they are appropriate.

Once initial impressions are formed we act to conserve them

To summarize the research described so far, people tend to form initial impressions very rapidly and typically on the basis of inadequate evidence. That in and of itself is not such a bad thing, if only they would then search for additional evidence and keep their minds open to changing their opinion. Unfortunately, the opposite appears to be true. After forming an initial impression, people tend to seek evidence to support that belief rather than seeking evidence in an unbiased fashion. Wason[21] demonstrated this phenomenon very clearly and it has been replicated and extended frequently since (cf. Wason and Johnson-Laird)[21] Subjects were told that the three numbers 2, 4, 6 conformed to a simple relational rule. Their job was to discover this rule by generating triads of numbers. After each triad they were told whether the triad conformed to the rule. They were allowed to keep records on paper and were to show the rule to the experimenter only when they were highly confident that they had discovered it. Very few people get the rule correct on the first try. Of forty-five scientists and ministers in Mahoney and DeMonbreun's study,[22] only two discovered the rule on their first guess. Fewer than half ever found the right rule. Why is this task so difficult? It is because people are likely to form an initial hypothesis very quickly – that the rule is "increasing by twos" or "even numbers." They then spend their time creating tests that would confirm their hypothesis, e.g., 100, 102, 104. Other rules are, of course, possible, including the correct rule: "numbers increasing in order of magnitude." To test whether this alternative

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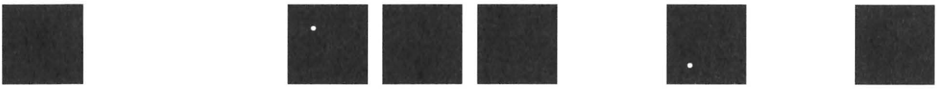

39 million 840,000

Now the photon
is on the outskirts of our galaxy
near a dwarf companion.
Three years before our photon gets
to this little irregular galaxy
known as the Large Magellanic Cloud,
a star in it explodes.
Billions of neutrinos
rush with billions of photons
toward earth,
creating for modern astronomers
one of the most exciting and
scientifically fruitful events of the century.

There will be a few seconds
on February 23, 1987
when billions of neutrinos
pass through our bodies –
many more than is normal –
so many more
that some of the neutrinos
may actually collide
with the atoms in some of us,
an almost unheard of event.

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23
Mynatt, J.C., M.E. Doherty and R.D. Tweney. 1977. Confirmation bias in a simulated research environment: An experimental study of scientific interference. *Quarterly Journal of Experimental Psychology*, 29, 85-95. See also Mynatt, J.C., M.E. Doherty and R.D. Tweney. 1978. Consequences of confirmation and disconfirmation in a simulated research environment. *Quarterly of Experimental Psychology*, 30, 395-406. See also Wason and Johnson-Laird, 1972, cited in 21.

24
Snyder, M. and W.B. Swann. 1978. Hypothesis-testing processes in social interaction, *Journal of Personality and Social Psychology*, 36. 1202-1212.

25
M.J. Mahoney. 1977. Publication prejudices: An experimental study of confirmatory bias in the peer review system. *Cognitive Therapy and Research*, 1, 161-175. See also Mahoney and DeMonbreun, 1977, previously cited in 22. Also Mitroff, I.I. 1974. Norms and counter-norms in a select group of Apollo moon scientists: A case study of the ambivalence of scientists. *American Sociological Review*, 39, 579-495.

26
See Snyder and Swann, 1978 (Experiment 3), previously cited in 24.

27
Snyder, M. and B. Campbell. 1980. Testing hypotheses about other people: The role of the hypothesis. *Personality and Social Psychology Bulletin*, 6, 421-426.

28
Mynatt, Doherty and Tweney, 1978, previously cited in 22.

29
Anderson, 1983, previously cited in 15. Also Anderson, C.A., M.R. Lepper and L. Ross. 1980. Perseverance of social theories: The role of explanation in the persistence of discredited information. *Journal of Personality and Social Psychology*, 39, 1037-1049.

30
Chapman, L.J. and J.P. Chapman. 1967. Genesis of popular but erroneous psychodiagnostic observations. *Journal of Abnormal Psychology*, 72, 193-204. Chapman, L.J. and J.P. Chapman. 1969. Illusory correlation as an obstacle to the use of valid psychodiagnostic signs. *Journal of Abnormal Psychology*, 74, 271-280.

31
For an extensive overview, see Lichtenstein, S., B. Fischhoff and L.D. Phillips. 1982. Calibration of probabilities: The state of the art to 1980. In D. Kahneman, P. Slovic and A. Tversky, eds. *Judgment under uncertainty: Heuristics and biases.* Cambridge, Massachusetts: Cambridge University Press, 306-334.

32
Kahneman, D. and A. Tversky. 1973. On the psychology of prediction. *Psychological Review*, 80, 237-251. Also Oskamp, S. 1965. Overconfidence in case-study judgments. *Journal of Consulting Psychology*, 29, 261-265. Sines, L.K. 1959. The relative contribution of four kinds of data to accuracy in personality assessment. *Journal of Consulting Psychology*, 23, 483-492.

rule might be correct, subjects would have to use a disconfirmation strategy, e.g., seeing if the sequence 10, 11, 12 conformed to the rule. People rarely do this. Even when they are told "even numbers" is incorrect, the majority persevere in their error by reconfirming their previously falsified hypothesis.

The Wason research may seem like a "straw-man task," because it was selected to mislead, that is, the rule most obvious to most people is incorrect and a less obvious rule is correct. This argument should give us little comfort, however, for two reasons. First, many situations in the real world are misleading in the same way. Second, other research has shown the same phenomenon in other situations as well.[23] For example, Snyder and Swann's Experiment 1[24] asked college students to test the hypothesis that a target person was either an extrovert or an introvert. The subjects tested the hypothesis by selecting questions to ask the target person. Those who were asked to test the target person's extroversion selected questions that solicited evidence of extroverted behavior. Those testing the target person's introversion tended to ask questions that probed for introverted behavior. Thus, the subjects had no preexisting tendency to favor extrovert or introvert, yet they probed only for information that would support the hypothesis, ignoring the possibility that alternative hypotheses might be true.

This tendency to seek confirmatory evidence and not disconfirmatory evidence has been demonstrated even among research scientists, who ought to know better.[25] Furthermore, variables that one would expect to reduce the confirmatory bias have been shown to have little effect. For example, the phenomenon occurs even when the expected accuracy of the hypothesis is low,[26] when the initial hypothesis contains information about disconfirming as well as confirming attributes,[27] and even when the subjects have been trained to use disconfirmation.[28]

The confirmatory bias is so strong that

a *initial impressions last even if people are told that the data they had just studied were false*[29] *and*

b *people find data that support their hypotheses even when the data provided contains no systematic support for that hypothesis.*[30]

We can not even rely on our sense of confidence

To make matters worse, it appears that these errors of reasoning are accompanied by a remarkable overconfidence in their validity, particularly when the judgment is difficult.[31] Not only do humans show a general tendency toward overconfidence, that overconfidence can be increased by invalid factors:

- Additional, redundant information makes people more confident even when it does not increase the actual probability of being correct[32]

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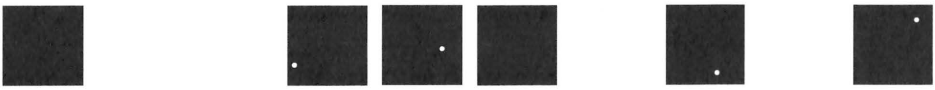

39 million 975,000

(Neutrinos are so close
to being nothing at all
that they usually
pass through things –
even millions of miles of lead
without any collisions.)
Where were you February 23, 1987?
Did you feel anything different?
But back to our photon's journey.
There are no astronomers on earth now,
but there are woolly mammoths.
And in just 50,000 years or so,
the stars will arrange themselves
into the familiar constellations
that man has known
throughout the time
when he has built
a collective memory
through writing and pictures
and stories.

The universe
the photon now passes through
is more crowded.
It occasionally comes near star cities
that while smaller than galaxies
are no less dramatic.
These are the globular clusters,
such as M-13 in Hercules.
This is one of the most spectacular objects
I can see in my telescope
and pictures can't do it justice,
for in the pictures,
you miss the dimension
of varying brightness –
of dozens of bright jewels
scattered over a glistening background
of fainter ones.

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33
Langer, E.J. and J. Roth. 1975. The effect of sequence of outcomes on a chance task on the illusion of control. *Journal of Personality and Social Psychology*, 32, 951-955.

34
Fischhoff, B. 1977. Perceived informativeness of facts. *Journal of Experimental Psychology: Human Perception and Performance*, 3, 349-358.

35
Fischhoff, B. 1982a. For those condemned to study the past: Heuristics and biases in hindsight. In D. Kahneman, P. Slovic and A. Tversky, eds. *Judgment under uncertainty*. New York, New York: Cambridge University Press, 335-351.
Fischhoff, B. 1975. Hindsight ≠ foresight: The effect of outcome knowledge on judgment under uncertainty. *Journal of Experimental Psychology: Human Perception and Performance*, 1, 288-299.
Fischhoff, B. and R. Beyth. 1975. "I knew it would happen" – remembered probabilities of once – future things. *Organizational Behavior and Human Performance*, 13, 1-16.

36
Slovic, P. and B. Fischhoff. 1977. On the psychology of experimental surprises. *Journal of Experimental Psychology: Human Perception and Performance*, 3, 544-551.

37
Einhorn, H.J. and R.M. Hogarth. 1978. Confidence in judgment: Persistence of the illusion of validity. *Psychological Review*, 85, 395-415.

- Early success on a task increases overconfidence whereas early failure leads to more accurate prediction[33]

This overconfidence also affects even our memories of what we believed before we discovered an answer. For example, Fischhoff[34] asked people to rate the probabilities of two alternatives to factual questions (e.g., Was Aladdin of the magic lamp a) Chinese or b) Persian?). Then they were told the answer (Aladdin was Chinese). Finally, they were asked to remember what their initial probabilities were. For those questions with surprising answers (i.e., those most subjects had wrong), subjects misremembered how wrong they were. Fischhoff and his colleagues have demonstrated the same "I knew it all along" tendencies with historical events[35] and with learning of experimental results.[36]

Why should we be so overconfident? Part of the reason seems clearly to be because we are focusing on the evidence in our favor and not considering inconsistent or missing data.[37] A classic example is in personnel decisions. Say, for example, one hires new college graduates on the basis of their grade point average. Two years later one discovers that most of the people hired on that basis are performing well and the personnel office concludes that grade point average is a good criterion for hiring. One problem with this conclusion is that no information is available for those whose grade point averages were below the cutoff. If a higher proportion of people with low grade point averages would have succeeded than the proportion of those with high grade point averages, the personnel office would surely change its criteria. Yet, lacking half the evidence, the personnel department people become more confident.

We make causal connections impressionistically

Impressionistic reasoning also leads to errors in causal analysis. As an example, consider Designer A who creates graphic X, which is shown to result in all twenty-five college students in class C understanding the principle (notice that the typicality problem of case studies is solved in this example). Designer A then concludes that the effectiveness of design is due to the way he used color. This conclusion may reflect Designer A's intentions for this graphic and his beliefs about the effectiveness of design, but it may not reflect reality. Even asking the students may be ineffective, because people are not always aware of their own thought processes. The only way to find out whether it is really the use of color that makes the design effective is to compare the effectiveness of A's design with a comparable design that uses colors in other ways. Although this may seem like nit-picking to practitioners who would rather get on with their work of designing, it is an important issue. Without such knowledge, Designer A will continue to produce designs that use color comparably and may or may not continue to use the factors that really made the design effective. He is bound to meet with mixed success.

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M-13

No fewer than a million stars
are packed into a sphere
with about one star per
cubic light meter.
That's far closer than the stars are
around us,
yet you must understand
that while this is close for stars,
it is not really very close.
Robert Burnham, Jr.,
in his wonderful
Celestial Handbook,
describes this scale model
of M-13.
Take a million grains of sand
to represent the million stars in the cluster.
Let them occupy a volume of space,
roughly 300 miles on a side.
Each grain, just 3/100ths
of an inch in diameter,
is separated from
the next nearest grain
by three miles!

So these clusters,
which appear to be
the most densely packed mass of stars
in the universe to us,
are separated
by unimaginable distance.
A globular cluster
is mostly empty space
and our photon
could easily pass through one
without encountering
anything.
Neanderthal man has
disappeared.
The first musical instruments
have been crafted.
Farming will start soon,
and in a few thousand years,
people will begin
to populate America.

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38
Nisbett, R.E. and E. Borgida. 1975. Attribution and the psychology of prediction. *Journal of Personality and Social Psychology*, 32, 932-943.

39
Further examples include diagnosis and prognosis in mental patients, see Dawes, R.M., D. Faust and P.E. Meehl. 1989 Clinical versus actuarial judgment. *Science*, 243, 1663-1674. See also Sawyer, J. 1966. Measure and Prediction: Clinical and Statistical, Psychological Bulletin, 66, 178-200. Turk, D.C. and P. Salovey. 1988. *Reasoning, Inference and Judgment in Clinical Psychology.* New York: Free Press. In medical science, see Eddy, D.M. 1982. Probabilistic reasoning in clinical medicine: Problems and opportunities. In D. Kahnemman, P. Slovic and A. Tversky, eds. *Judgment Under Uncertainty: Heuristics and Biases.* Cambridge, Massachusetts: Cambridge University Press, 249-267. Kleinmuntz, B. 1984. The scientific study of clinical judgment in psychology and medicine. *Clinical Psychology Review*, 4, 111-126. Regarding making decisions or judgments about oneself, see Nisbett, R.E., E. Borgida, R. Crandall and H. Reed. 1976. Popular induction: Information is not necessarily informative. In J.S. Carroll and J.W. Payne, eds. *Cognition and Social Behavior*, 113-133. Hillsdale, New Jersey: Erlbaum.

Statistical evidence is often ignored and misunderstood

Much of the research described so far has involved designs that contrasted impressionistic data (representativeness, available memories, stereotypes, case studies) to statistical data. These studies have shown that when people have access to both impressionistic data and statistical data, most ignore the statistical data and form their predictions or conclusions on the basis of the impressionistic data.

A particularly nice example of this is a study by Nisbett and Borgida.[38] They asked college students to predict how people would act in a psychology experiment in which the subjects would be subjected to painful electric shock. Some subjects were provided with a table of the following data about people's behavior in this experiment: two refused to participate, one stopped the shock at tingling fingers, six stopped the shock at a jolt felt through the whole hand, nine stopped the shock at a jolt causing hand and forearm to jerk, and sixteen went all the way to a jolt causing entire arm to jerk. When later asked to predict how thirty-two new people would respond, they produced a distribution that was quite similar to the data they had been given and was quite unlike the guesses of other subjects who had not been given the table of data. This shows that they did understand the statistical information and could remember and use it appropriately. In contrast, when they were asked to predict the behavior of individuals whom they had seen on videotape or about whom they had read descriptions, they did not make use of the tabled information – they did not guess that the person would accept the most severe shock. In fact, their responses were no different than the responses of people who had not seen the tabled data. Thus, these subjects did not use the statistical information they clearly had assimilated. In contrast, in the same study subjects who were given two case studies of people who took the extreme shock *did* predict that target individuals would take the extreme shock. Thus, the subjects in this study used case study data to predict behavior, but did not use tabled data to make predictions even though they remembered the data.

Similar tendencies to disregard statistical evidence have been found in hundreds of studies in a wide range of situations – predicting people's behavior, as the Nisbett and Borgida study did,[38] assigning people to categories, as the Kahneman and Tversky study did,[32] forming causal hypotheses, as Anderson's study[15] of the causal relation between being a good firefighter and a risk-taker did.[39] Even when they know better, people prefer to base their judgments on impressions rather than statistical evidence.

Why is Statistical Information Superior?

Although reasoning on the basis of impressionistic data has its place, that place is decidedly *not* when statistical evidence is available. To see how reasoning from impressionistic rather than statistical data can

Table 1 Firefighters and Risk

Case	Job excellence	Risk taking	Case is consistent with hypothesis that good firefighters are:
1	Poor	High	Low risk takers
2	Poor	High	Low risk takers
3	Poor	High	Low risk takers
4	Good	High	High risk takers
5	Good	Low	Low risk takers
6	Good	Low	Low risk takers
7	Good	High	High risk takers
8	Poor	Low	High risk takers
9	Poor	Low	High risk takers
10	Poor	High	Low risk takers

40
Tversky, A. and D. Kahneman. 1971. Belief in the law of small numbers. *Psychological Bulletin*, 76, 105-110.

lead us to error, consider the example of Anderson's firefighter case studies, described earlier. Recall that one of the firefighters was both good in his job and a high risk-taker and the second firefighter was both weak in his job and a low risk-taker, thus suggesting that good firefighters are high risk-takers. The problem with the case studies is that they may be typical or atypical cases. It may be much more common for a good firefighter to be a low risk-taker, but we have no way of telling that from the two case studies. There is no reason to believe and no way to predict whether two case studies will be typical of the population or not. Thus, for any two case studies that suggest a particular relation (e.g., that good firefighters are high risk-takers) the true relation may be

a *the one illustrated by the case studies,*
b *opposite to the case studies,*
(i.e., that good firefighters are low risk-takers) or
c *that there is no relation between risk-taking*
and excellence in fire fighting.

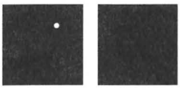
Because research has made it clear that even scientists steeped in statistical knowledge make this mistake,[40] I will demonstrate it with an example. I have created a sample of ten purported case studies of risk-taking in firefighters (*see table 1*). It shows, for example, that Case 1 was a poor firefighter who was a high risk-taker, and Case 5 was a good firefighter who was a low risk-taker. A person who knows only these two cases would likely believe the hypothesis that good firefighters are low risk-takers, because both cases are consistent with that hypothesis. A person who is exposed only to Cases 4 and 8, would be likely to conclude the opposite (that good firefighters are high risk-takers). A person who see only Cases 1 and 4 would probably conclude that there is no relation.

In this "manufactured" example, in fact, the true situation is that there is no relation between risk-taking and fire fighting job performance. The case studies were generated by tossing coins. The first toss came up tails and so Case 1 became a poor firefighter. The second toss came up heads and so Case 1 was a high risk-taker. The third toss was tails and so Case 2 was a poor firefighter, etc. Thus, the data were completely random.

What can we conclude from this example? If we reason from only a few case studies, the conclusion we reach will depend on the particular cases we see. If, in contrast, we pay attention to the entire set of ten case studies, we would be much more likely to reach the correct conclusion that there is no relation, because six case studies suggest the first and four, the second.

Note, however, that the appropriate conclusion may not be clear even if the kind of data in table 1 is available. In the situation given, which was created by chance, the lack of a relationship was fairly obvious, but what if seven cases supported one hypothesis and three, the other. Would you be willing to conclude that the hypothesis was supported, or would you want to conclude that it was just random variation? It is to answer such questions that statistical techniques were developed (and the

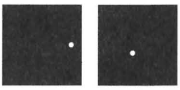
Continued from page 338.



39 million 994,000

The photon now passes
the remnants of an exploded star.
Many know this ragged gas cloud
as the Crab Nebulae, or M-1.
Roughly 7,000 years ago,
it exploded. The light from the explosion
reached us about 1,000 years
ahead of our Kamikaze Photon.
The cloud of gas and dust
is expanding at the rate
of about 600 miles a second.
Moving at 186,200 miles a second,
our photon easily leaves
the remnant of the exploded star
behind.

39 million 998,000



Soon
the Kamikaze Photon
passes the Great Orion Nebulae.
On Earth men in the Near East
are writing about the birth of a savior
in Bethlehem.
Another type of birth
is taking place
in the gas and dust
of the great Orion nebulae,
for there we have seen stars being formed.
In even the smallest telescope,
this nebulae is a spectacular sight
and it is not hard to imagine
from these views
that it is a seething mass
of activity.
The truth is,
that while matter here
is relatively densely packed,
a small sampling of it
would show that it is really
closer to a vacuum
than anything
we've been able to create
in the laboratory
on Earth.

Continued on page 344.

41
Fischhoff, 1977; previously cited in 34. Also Kurtz, R.M. and S.L. Garfield. 1978. Illusory correlation: A further exploration of Chapman's paradigm. *Journal of Consulting and Clinical Psychology*, 46, 1009-1015. Wood, G. 1978. The knew-it-all-along effect. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 345-353.

42
Fischhoff, B. 1982b. Debiasing. In D. Kahneman, P. Slovic and A. Tversky, eds. *Judgment Under Uncertainty*. New York: Cambridge University Press, 422-444. Lichtenstein, Fischhoff and Phillips, 1982, previously cited in 31. Calibration of probabilities: The state of the art to 1980, previously cited in 31.

43
Fischhoff, 1982 b, just cited, and Lichtenstein, Fischhoff and Phillips, 1982, previously cited in 31.

44
Koriat, A., S. Lichtenstein and B. Fischhoff. 1980. Reasons for confidence. *Journal of Experimental Psychology: Human Learning and Memory*, 6, 107-118.

45
Fazio and Zanna, 1981, previously cited in 17. Also Zanna, M.P., J.M. Olson and R.H. Fazio. 1981. Attitude-behavior consistency: An individual difference perspective. *Journal of Personality and Social Psychology*, 38, 432-440.

answer in this case is that seven of ten trials is most likely to be due to chance variation, not a true relation).

The relevance of this to the situation of creating visual designs is obvious. Most designers have only case study information – the opinions of oneself plus a few colleagues or target individuals. Their opinions may be typical of the larger audience or they may be atypical – the designer has no way of knowing.

Biases in reasoning are not easy to overcome

People can not overcome their judgmental errors simply by becoming aware of them. Studies in which errors were explained to individuals and they were warned against them have been ineffective in correcting errors.[41] Nor does education nor expertise per se overcome these biases in reasoning. Physicians, clinical psychologists and stock analysts have all been shown to make grave errors in judgmental reasoning. The only professionals who have been found to be accurate predictors are weather forecasters and horse-racing columnists.[42] Unlike therapists, personnel officers and designers, these forecasters have available to them feedback about their predictions. Weather forecasters find out if their prediction of rain was correct and horse-racing columnists find out how the race turned out. Most practitioners do not get such consistent feedback.

Experimental studies have delineated exactly what kinds of information effectively curb biases:

- consistent and specific feedback[43]
- searching for counterevidence or alternative hypotheses, that is, exceptions to one's beliefs[44]
- searching for a complete picture of the situation by attending to a variety of instances (e.g., ten designs in different contexts rather than just one).[45]

This research suggests that if designers are drawing on their entire experience to form a conclusion (for example, whether in their experience asymmetrical designs are truly more aesthetically pleasing), it might help to make a list of all the times they've made such designs and whether the designs were pleasing to them and effective with their audience. It is particularly important to look specifically for contrary examples – designs in which the asymmetrical design is less aesthetically pleasing. Such a list will help to correct for many biasing factors – the first and last cases, extreme cases, and cases that confirm one's preconceptions.

Making a list of one's past experiences will, of course, not solve the problem of not knowing the thoughts and reactions of consumers of graphics. The unbiased, accurate way of forming judgments about people, about causal relationships (such as the comprehensibility or emotional impact of a graphic on people) is to use quantitative information about large groups of individuals. Humans are naturally capable

Continued from page 342.

39 million 999,500

About the time
that Columbus was rediscovering
America for the Europeans,
the Kamikaze Photon
was passing Antares,
a red giant and
one of the brightest stars
in our sky.
This also happens to be the distance –
about 500 light years –
where our distance measurements
become much more accurate.
From this point,
inward careful observation
and simple trigonometry
can tell us
how far away a star is
with some measure
of precision.
Of course,
it will still be another 100 years
before anyone turns a telescope to the sky.
People still believe
that the Earth is the center
of the universe
and that the stars are out
just beyond the planets
which are, themselves,
believed to be quite close.
With Copernicus, Galileo,
and Kepler,
that will change
and with the new knowledge
will come dramatic changes in philosophy,
art, and religion,
not to mention exploration
and mechanics.

39 million 999,933

Photos taken
through the new 100-inch telescope
on Mt. Wilson in California
convince scientists
that the so-called "spiral nebulae"
are really distant galaxies.
In another decade or so,
they will be studying
a phenomena known as the "red shift"
and will use this to discover
that the spiral known as M-104,
the Sombrero,
is 40 million light years away,
give or take a million or two.

Continued on page 346.

46
With scientists,
see Tversky and
Kahneman, 1971,
previously cited in 40;
with physicians,
see Eddy, 1982,
previously cited in 39.

of learning to reason statistically – after all, humans developed the various quantitative techniques – but, even highly trained and experienced people[46] will take every opportunity to ignore the statistical information and resort to their impressionistic, rule-of-thumb judgmental processes. The inescapable conclusion is that one can not trust one's own intuitions about the graphic's effectiveness, one can not rely on expert opinion (since the expert is also biased), and one can not even depend on trying out the graphic with a few individuals, because that amounts to reliance on case study evidence.

Conclusions: Human Reasoning

The research on human reasoning is quite clear. People form beliefs very quickly, on the basis of

a *their own limited experience,*
b *their understanding of expert opinion,*
c *their acquaintance with a few relevant individual cases and*
d *whatever melange of these various kinds of information is uppermost in their minds.*

Once such a belief is formed, people assimilate additional information to it and with each new piece of information they become more confident in that belief. They show a profound lack of ability to differentiate between more or less valid data and show a remarkable tendency to ignore statistical data even though it is almost always more accurate. They tend neither to seek nor accept disconfirming evidence, even when it is hammered at them. It should come as no surprise that there are so many instances of major errors in all walks of life – business, engineering, science, parenting, etc.

Note that the use of these heuristics is not evidence that human minds are disordered or irrational. These are typically human cognitive processes and they are quite effective in situations that call for rapid, common sense judgments. In our evolutionary past, such judgments – deciding whether a sound or sight was, for example, prey or predator, friend or foe – could be life-saving. This same reasoning, however, becomes biasing when we need to make judgments about frequency of events, covariation or cause in situations in which one case varies from others. Judging (or predicting) the effectiveness of designs is one of these situations, because it always involves a target audience of a large number of people who will react in varying fashions. Reasoning on the basis of only partial data – one or two individuals or only one aspect of their behavior – will in most cases lead to error. In such judgment situations reasoning on the basis of judgmental heuristics will always be inferior to reasoning on the basis of statistical principles.

Continued from page 344.

39 million 999,950

And still the photon moves on.
It is 1941 and the photon
is now near Castor,
a bright star
in the constellation Gemini,
the heavenly twins.
And in a hospital
in Baltimore, Maryland,
I open my eyes and become aware.
These two seemingly unrelated events
will eventually come together
and in the end
annihilate the photon,
stopping at last
its 40 million year
odyssey.

39 million 999,989

Ronald Reagan comes to power
as one of America 's
most popular presidents.
The photon
is approaching the
neighborhood of Sirius,
the brightest star
in our winter sky.

39 million 999,995

As Ronald Reagan makes deals or
doesn't make deals with Iran
to free hostages
and Ollie North does his thing
with the Contras,
the photon
reaches the distance
of our nearest stellar neighbor,
Alpha Centauri.
This double-star system
is just 4.3 light years away.
That may seem awfully close
in terms of what we've been discussing
and it is from the perspective
of our long-traveling photon.
But the photon still has
roughly 25,000 billion miles
to go!

Continued on page 348.

What can be done?

Simply becoming aware that one's reasoning is flawed is not sufficient to overcome the tendency to make faulty judgments. How then can designers increase the likelihood that they will avoid mistakes such as the DC metro signage and increase the probability of effective design? It is possible to take corrective measures, but only by collecting information systematically and using all of the data thus collected. Two methods – scientific investigation and user-based design – provide frameworks by which human errors in reasoning can be addressed. I will first discuss why designers should learn about scientific research concerning visual representations and then describe illustrative research on using visual representations to promote learning. Last I will discuss the use of user-based design techniques, which allow practitioners to incorporate systematic exploration of the users into the development of the design.

Scientific investigation

The discussion on human reasoning should have made it clear that scientists are human and thereby vulnerable to all the same reasoning tendencies as the rest of humankind. This does not mean, however, that conclusions made on the basis of scientific evidence are no better than those made by humans – scientist or other – in their normal functioning. The scientific method has, in fact, developed as a means of correcting for human error by building in constraints against such error. For example, conclusions considered scientifically valid are based on the responses of large and representative samples of individuals; the use of such samples guards against errors likely to result from reasoning on the basis of a few individuals.

Nonetheless, the scientific method is not infallible. The scientific study of human behavior has a number of characteristics that should be understood if one is to be able to interpret the research results appropriately. It is beyond the scope of this article to review all of the issues of validity, although it behooves those who wish to evaluate the evidence for themselves to learn about these issues. For the purpose of this paper, I will focus on general characteristics of scientific research that need to be understood to interpret a group of related studies:

- The resulting knowledge is probabilistic – when describing psychological responses relevant to design issues there is very little that can be said to be true of all humans and so hypotheses must be tested in terms of what is true of most people. Finding one person who does not conform to the hypothesis does not disprove the hypothesis.
- The method of study of human behavior is probabilistic – the statistical test that determines whether a particular hypothesis is supported by a specific set of data returns a probability of the hypothesis being valid. This means that even when a particular study is well done, its conclusions may be wrong. This is why scientists insist on replication of studies. Results from one study may be simply a chance phenom-

Continued from page 346.






39 million 999,997

39 million 999,999 Years 365 days 21 hours

When Governor Michael Dukakis
was perched at his apex –
just before one of the steepest,
longest, most dramatic slides
in American political history –
our photon was entering
the outer region
of the solar system.
It's a region known as the Oort Cloud
after the astronomer
who postulated
its most likely existence.
This is a dark area
of interstellar space
where dark comets swarm.
Every once in a while
the orbit of one of these comets
carries it in from the Cloud
and it burns a path
across our night skies
on its way to a close encounter
with our sun.
It is still a long way
from what we generally consider
the outer bounds of our solar system,
the orbit of Pluto.

In fact, it wasn't until
the spring Saturday in 1991
during the time I was having supper
that our Kamikaze Photon
passed the orbit of Pluto.
At 7:30 pm
some friends came out
to look through
the 16-inch telescope.

Continued on page 376.

47
Personal communication, Herbert Feigl, 1968.

48
See Tufte, 1990, 92-95, previously cited in 3.

49
For example, see Marr, D. 1985. *Vision.* San Francisco: W.H. Freemon, 215-233.

50
Marr, 1985, 94.

enon, but if two or three studies find the same results, the likelihood that the results are simply a chance phenomenon becomes vanishingly small.

- Although the scientific method builds in corrective factors, experimenter biases can still affect the results. Thus, replications that are done by different researchers in different laboratories are particularly desirable.
- In all studies of human behavior one may wish to test a general hypothesis, such as diagrams facilitate learning. To test such a hypothesis, one must, however, implement a specific situation. One must use a particular diagram (e.g., a representation of a "machine,") in a particular learning setting (e.g., the study of mechanics) and one must use a particular test of learning (e.g., solving a problem). Even if the specific experiment is replicated several times in two or more laboratories, it may only be true within the narrow confines of its particular features. The hypothesis may not be supported when a different kind of diagram (e.g., a graph) in a different learning situation (e.g., mathematics) with a different kind of learning (e.g., generating algebraic equations) is used.
- Scientific knowledge develops by the discovery of new data. At any point our beliefs may be shown to be incorrect by new information. As Herbert Feigl was fond of saying, scientific knowledge is only true until further notice.[47]

Thus, conclusions based on scientific studies are preferable to conclusions based without such research, but the development of useful principles requires a body of carefully executed, broad-ranging studies. Three examples of the kind of research evidence available follow.

Indirect Evidence: Studies of Perception

Psychologists have been studying how people perceive visual stimuli for one hundred years. One might expect it to be a rich source of information about the effectiveness of graphics. In one sense, that is quite true, but its evidence is indirect and thus insufficient by itself. An example will illustrate this.

Tufte[48] effectively used basic research on color perception to produce guidelines for use of color and contour. He warned against the use of value scales of color (e.g., progressing from light to dark blue) to represent differences in quantities, as is often done in topographic maps. He argues that because of color context effects, viewers may perceive particular colors inaccurately and thus interpret the quantitative information inaccurately. He then suggests that this problem might be solved by drawing light contour lines coincidental with color changes. His reasoning here is that, because humans are apparently wired to perceive contour edges preeminently,[49] drawing in contour lines makes each color code a coherent whole, "minimizing within-field visual variation and maximizing between-field differences."[50]

There are two problems with Tufte's use of perception research here. First, Tufte was not consistent in his use of perceptual prin-

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51
For example, see Rosenblith, J.F. and J.E. Sims-Knight. 1984. *In the Beginning: Development in the First Two Years of Life.* Monterey, California: Brooks/Cole.

52
For extensive examples of this, see Macdonald-Ross, M. 1977b. Graphics in Text. In L.S. Shulman, ed. *Review of Research in Education* (volume 5), Itasca, Illinois: Peacock, 45-85.

ciples. He used the color contrast phenomena effectively, but recommends using light, thin contour lines even though perceptual principles suggest that darker, more prominent contours would be more easily perceived.[51]

If perceptual principles are an appropriate basis for design decisions in one instance, why are they inappropriate in another instance?

The second problem is that the perception literature permits us to generate hypotheses about effective design, but it does not permit us to assume that such hypotheses are valid without conducting direct experimental tests. In the Tufte example, drawing light contour lines might not be sufficient to counteract successfully the color context effects. Worse, contour lines may be sufficient with some color combinations and not with others.

This illustrative example is decidedly not meant to argue against the value of perception research in guiding design research.[52] Rather, it only argues that indirect application of scientific evidence is just a start, not a final goal.

Direct evidence: Research on visuals in texts

Scientific research has also directly tested the effectiveness of particular kinds of visual representations. For example, there is a large body of research concerned with the role of graphics in helping children to learn in school – to learn to read, to remember textbook material, to understand math concepts, etc. Most of this research is atheoretical. It typically starts with a study that compares a text with a visual to a text without. The second step is to find if the study was valid – subsequent researchers correct flaws in its methodology and repeat the study to see if they get the same results. If so, the study is said to replicate. The third step is to see how widely appropriate the conclusion is. Is it true for a variety of pictures? Is it true for both introductory and more advanced texts, both with and without a text, at the beginning, middle or end of the text? Is it true for both concrete illustrations and diagrams, for memory and for problem solving, for all children or just some (good readers, poor readers, high ability, etc.), is it true for all content areas (e.g., social studies, mathematics) or only for some? Confident conclusions require that the preponderance of studies of a particular sort (specified types of graphics, content areas, etc.) reach the same conclusion. Often the answer is complex – what is true for one kind of visual is not true for another, etc. Sometimes these complexities lead to the formulation of theoretical principles that describe why and when visuals will be effective.

The scientific study of the effect of visuals on learning is following this course. Some of the possible situations have been extensively studied and have yielded consistent findings from different laboratories with different instantiations. Thus, one can have some confidence in the validity of the resulting conclusions. This is true for research on the effect of pictures on memory. The other research areas described here

Figure 1 **A comparison of organizational and interpretational illustrations.**

Example from Levin, Anglin, and Carney, 1987.
Reprinted with permission from *Alive and well: Decisions in health.* by A. Eisenberg and H. Eisenberg, 1979, New York: McGraw-Hill.

Figure 1.1 **An organizational illustration:**
Notice that it separates the procedures into discrete units and then puts them together in an ordered sequence.

Open the airways by placing one hand under victim's neck and the other on his or her forehead, tilting back the head to lift the tongue from the back of the throat. Remove any obstructions - solids, liquids, vomitus. If the victim is not breathing, proceed to step 2.

If no pulse can be felt strike a sharp, quick single blow to the mid-chest with the fleshy portion of your fist, starting 8 to 12 inches above the chest. This must be done within 60 seconds of cessation of heartbeat.

To restart breathing, pinch nostrils closed, put your mouth over victim's to form tight seal, and inflate lungs with four quick, full breaths, without waiting between breaths. If no pulse is felt, proceed to step 4. Otherwise continue rescue breathing 12 times a minute until breathing resumes or help arrives.

Begin CPR. If alone, use 15 chest compressions (80 per minute) as shown in drawing 6, followed by 2 very quick inflations of victim's lungs as shown in drawing 3.

If you have help, begin CPR in a 5 to 1 ratio - 5 chest compressions to 1 lung inflation, without pause.

Effective cardiac compression in adult requires enough pressure to depress sternum (breast bone) at least 1 1/2 inches. Hold fingers free of chest wall.

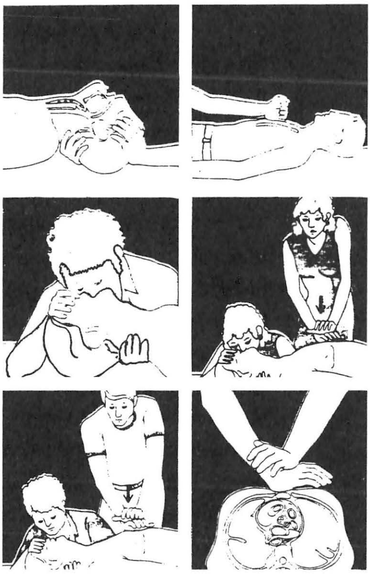
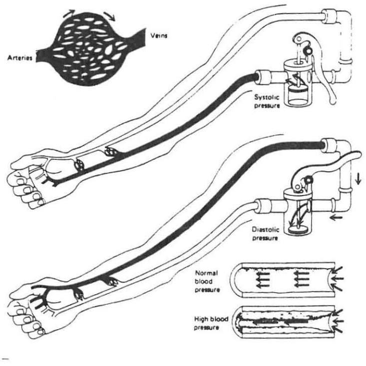


Figure 1.2 **An interpretational illustration:**
It makes the abstract concepts of heart functioning concrete and visual by superimposing the analogy of a pump onto the circulatory system.

The mechanics of blood pressure. When the heart is pumping blood into the circulatory system, blood pressure is at its highest point and is called systolic pressure. When the heart is at rest and filling between pumping beats, blood pressure is at its lowest point and is called diastolic pressure.

High blood pressure (over 150 systolic and 95 diastolic in most people) occurs when the arteries become partially blocked, inflexible, or both, thereby increasing pressure in the arteries and making the heart work harder to pump blood through the system.



have been much less studied, but have still yielded consistent results and sometimes across laboratories and so deserve some commendation.

Pictures and memory

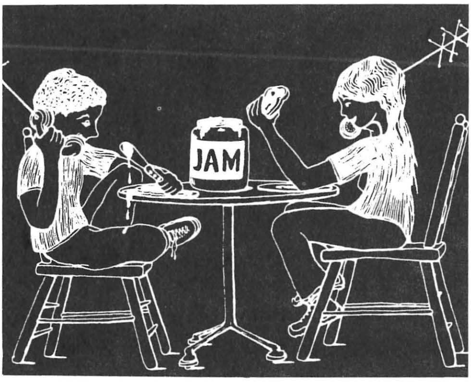
One of the most widely studied areas of visual representation is that of exploring the impact of adding pictures to text. Much of the motivation for this research stems from research done in the 1960s that suggested that the pictures that accompany learning-to-read texts can interfere rather than facilitate children's learning to read.[53] At that time there were few studies that assessed the impact of pictures on older students' comprehension of text – so-called reading to learn – and so many people concluded that pictures in text are never beneficial.[54] Since that time hundreds of studies have addressed this issue and we can now reach some fairly clear conclusions.

As described above, to form conclusions one must honor differences in kinds of illustrations, in the proposed effect, and in the type of individual for whom a conclusion is appropriate. I will begin with the largest body of research – the effects of adding pictures to prose on students' ability to remember what they have read. Several reviews using a statistical summarizing technique called meta-analysis[55] have found that when pictures or diagrams relevant to a prose passage are presented, students are more likely to remember what they have read. In contrast, there appears to be equally consistent evidence that pictures that are merely decorative do *not* facilitate memory. The difference between a merely decorative picture and a representational picture is that the decorative picture may be connected to the text loosely (e.g., a picture of a sailing ship in a story about a sailor), but it does not represent anything that is happening in the story. It is the kind of picture an illustrator might produce if told to create a picture that piques student interest or increases sales. Representational pictures illustrate a major narrative event, that is, "they tell the story," at least in part. Illustrations of stories would clearly be representational if artists were told to draw a picture that depicts the gist of the story or a scene from the story. Such representational pictures help to organize into one integrated whole disparate pieces of information contained in sequential sentences in the prose. They further clarify spatial and other relational information, such as where various objects and people appear in a scene. Representational pictures may accompany expository prose as well as stories; they then serve to make the textual material more concrete.

Illustrations that make the text more coherent or more comprehensible rather than just more concrete are organizational or interpretational.[56] Both types integrate or organize various elements of the text, but they differ in that interpretative figures deal with unfamiliar, difficult concepts whereas organizational ones deal with simple or familiar concepts. Examples of organizational pictures are "how-to-do-it" diagrams (*see figure 1.1*) and illustrated maps.[57] Interpretational pictures clarify difficult-to-understand passages and abstract concepts and often serve as advance organizers (*see figure 1.2*). Levin, Anglin, and

Figure 2 An example of a transformational illustration.

The critical information to be learned is Karl Jansky invented an antenna for improving the quality of telecommunications. The visual recodes the unfamiliar name Jansky into the more concrete jam and then integrates jam, antenna and telephone (telecommunications) into a scene.



Reproduced from Levin, J.R., G.J. Anglin and R.N. Carney. 1987. On empirically validating functions of pictures in prose. In D.M. Willows and H.A. Houghton, eds. *The Psychology of Illustration* (volume 1, Basic Research). New York: Springer-Verlag, 51-85.

53
Samuels, S.J. 1970. Effects of pictures on learning to read, comprehension, and attitude. *Review of Educational Research*, 40, 398-407. Also see Rusted, J. 1984. Differential facilitation by pictures of children's retention of written texts: A review. *Current Psychological Research and Reviews*, 3, 61-71.

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Levin, J.R., G.J. Anglin and R.N. Carney. 1987. On empirically validating functions of pictures in prose. In D.M. Willows and H.A. Houghton, eds. *The Psychology of Illustration* (volume 1, Basic Research). New York: Springer-Verlag, 51-85.

55
See Levin, Anglin and Carney, 1987, just cited. Levie, W.H. and R. Lentz. 1982. Effects of text illustrations: A review of research. *Educational Communication and Technology Journal*, 30, 195-232.

56
See Levin, Anglin and Carney, 1987.

57
For How-to-do-it diagrams, see Kieras, D.E. and S. Bovair. 1984. The role of a mental model in learning to operate a device. *Cognitive Science*, 8, 255-273. Also Stone, D.W. and M.D. Glock. 1981. How do young adults read directions with and without pictures? *Journal of Educational Psychology*, 73, 419-426. For illustrated maps, see Dean, R.S. and R.W. Kulhavy. 1981. Influence of spatial organization on prose learning. *Journal of Educational Psychology*, 73, 57-64.

Carney's meta-analysis showed that all three of these text-relevant visuals (representational, organizational, interpretational) improve memory compared to no pictures (the effect size for each is around .75, a moderate but real improvement) whereas decorative pictures did not facilitate memory.

Levin, Anglin, and Carney identified a final type of text-relevant illustration – the transformational picture (*see figure 3*). This type of picture, not usually found in texts, is designed to impact students' memory directly. They target the critical information to be learned and

a *recode it into a more concrete and memorable (i.e., vivid and salient) form,*
b *relate the separate pieces of that information in a well-organized context and*
c *provide the student with a systematic means of retrieving the critical information when later asked for it.*

This type of picture was more effective than all other picture types in improving memory. The effect was strongest for children (effect size of 1.43, a very large effect) but was also substantial and greater than other types of pictures for adults (effect size of 1.04, still an impressively substantial effect).

Why should transformational pictures facilitate memory? To improve memory of otherwise unrelated ideas, two good techniques are to link the ideas together by

a *providing an elaborative context and*
b *making the unit salient and distinctive.*

It may also be that transformational pictures are particularly effective when the elements that have to be remembered are not easily integrated. The example in figure 2 would not be effectively illustrated by an organizational or interpretational figure.

One of the hidden issues in the study of effects of pictures is the relation between pictures and the viewer's own cognitive processes. One way we explore that is to have people produce their own images or pictures and compare its effect to that of pictures produced by others. When we do this, we find that transformational pictures (1.25) and interpretational pictures (almost 1.00) are still quite effective, but that the effectiveness of creating one's own representational and organizational pictures is less than when illustrations are provided. Nonetheless, only the representational effect is so small (effect size = .30) as to be possibly of little practical value. This pattern of results suggests that these types of illustrations do capture something real in terms of the viewer's own cognitions. It further suggests that providing pictures is a good idea, because

a *it ensures that visual representations will be available and*
b *viewers may encode something additional from the picture that they would not have put into their own image.*

58
Mayer, R.E. 1989. Models for understanding. *Review of Educational Research*, 59, 43-64.

59
Beveridge, M. and E. Parkins. 1987. Visual representation in analogical problem solving. *Memory and Cognition*, 15, 230-237. Also Kieras, D.E. and S. Bovair, 1984, cited in 57. Mayer, 1989, just cited. Moyer, J.C., L. Sowder, J. Threadgill-Sowder and M.B. Moyer. 1984. Story problem formats: Drawn versus verbal versus telegraphic. *Journal for Research in Mathematics Education*, 15, 342-351. See also Winn, 1987, cited in 6.

60
Gick, M.L. and K.J. Holyoak. 1980. Analogical problem solving. *Cognitive Psychology*, 12, 306-355; also their 1983, Schema induction and analogical transfer. *Cognitive Psychology*, 15, 1-38; Kulm, G., J.F. Lewis, I. Omari and H. Cook. 1974, January. The effectiveness of textbook, student-generated, and pictorial versions of presenting mathematical problems in ninth-grade algebra. *Journal for Research in Mathematics Education*, 5, 28-35. Mayer, R.E. 1976a. Comprehension as affected by the structure of problem representation. *Memory & Cognition*, 4, 249-255. Sims-Knight, J.E. and J.J. Kaput. 1983. Effects of natural language and image-based representation on translating between the symbol systems of natural language and algebra. In D.R. Rogers and J.A. Sloboda, eds. *Acquisition of Symbolic Skills*. New York: Plenum Press, 561-570.

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Hayes, J.R. and H.A. Simon. 1974. Understanding written task instructions. In L.W. Gregg, ed. *Knowledge and Cognition*. Hillsdale, New Jersey: Erlbaum. Kaplan, C.A. and H.A. Simon. 1990. In search of insight. *Cognitive Psychology*, 22, 374-419. Larkin, J.H. and H.A. Simon. 1987. Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11, 65-99. Simon, H.A. and J.R. Hayes. 1976. The understanding process: Problem isomorphs. *Cognitive Psychology*, 8, 165-190.

62
Hayes and Simon,1974; Kaplan and Simon, 1990; and Simon and Hayes, 1976, all just cited.

63
Kaplan and Simon, 1990, just cited.

64
Larkin and Simon, 1987, just cited.

Diagrams and problem solving

The research on the memory effect of graphics in instructional text is quite extensive and yields rather clear results. It has fulfilled many of the criteria for good scientific research described above – a number of methodologically good studies using a variety of different specific pictures and texts studied by a variety of different investigators. Still, it is limited in that the studies all measure memory. Thus, we know that visuals of certain types help children remember material, but that isn't all there is to learning. We also need to be able to apply what we know and to solve problems with the materials we use. In some sense these are the really critical questions, at least when we think beyond the narrow confines of school tests. Moreover, it is not necessarily true that what helps one remember will help one learn to apply the material. In fact, Mayer has shown in a number of studies[58] that visual models (organizational and interpretational pictures) help students to understand and to apply what they know, even while they interfere with verbatim recall (i.e., remembering exactly what was presented). Thus, it would be inappropriate to assume that if visuals of certain types facilitate memory, they will facilitate all positive outcomes.

Fortunately, a number of research studies have addressed the issue of whether visual representations facilitate problem solving, usually using diagrams of some sort. Many have shown that when visual diagrams accompany text, problem solving is facilitated[59] but some studies have found no facilitative effect.[60] When scientific studies yield inconsistent results, it suggests that additional factors lurk behind the scenes.

Luckily, some research offers insight into when a visual will work. Simon and his collaborators[61] have developed a description both of the typical problem solving process and of the role visual representations can play in facilitating finding a solution. He argues that discovering an effective problem representation is the key to creative problem solving (that type of problem solving in which we gain a feeling of "Aha" when we finally understand how to solve it). When first confronted by difficult problem situations (one in which the solution is not obvious), individuals do not initially identify alternative problem representations and choose the best one. Rather they almost always adopt the representation suggested by the verbal problem statement.[62] If that representation is inappropriate, they must then find an appropriate problem representation to solve the problem. Once they find this alternative representation, they can solve the problem.[63] Obviously, then, a visual can help when it helps the individual formulate that better representation.

Diagrams as guides for search. Larkin and Simon[64] used a computational analysis to identify when and why a diagram would be a better representation of a problem than a verbal description. They identified two situations in which visual diagrams are superior. One is when search for the appropriate aspect of the problem is made easier by a visualization. They give an example of a physics problem (*see figure 3*)

Figure 3 **A demonstration of the value of a diagram as a guide for search.**

Verbal Problem:

We have three pulleys, two weights and some ropes, arranged as follows.

1

The first weight is suspended from the left end of a rope over Pulley **A**. The right end of this rope is attached to, and partially supports, the second weight.

2

Pulley **A** is suspended from the left end of a rope that runs over Pulley **B**, and under Pulley **C**. Pulley **B** is suspended from the ceiling. The right end of the rope that runs under Pulley **C** is attached to the ceiling.

3

Pulley **C** is attached to the second weight, supporting it jointly with the right end of the first rope.

The pulleys and ropes are weightless; the pulleys are frictionless; and the rope segments are all vertical, except where they run over or under the pulley wheels. Find the ratio of the second to the first weight, if the system is in equilibrium.

Visual Representation:

(the diagram of a concrete problem)

Schematic diagram:

(figure 2 in Larkin and Simon)

The subject solves the problem by going up from **a** to **b** to **d**, etc., e.g.:

1

A weight at **a**, with associated value **1**, hangs from something at **b**, which is a rope. Therefore the rope at **b** has associated value **1** (by the single-string support rule that says that if there is a single support, it will have tension equal to the value of the weight). Attention is now at **b**.

2

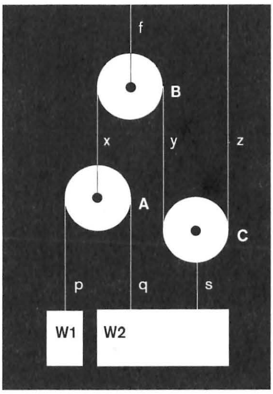
The rope at **b** is in the pulley-system at **d** which also contains the thing at **c** which is a rope. Therefore the rope at **c** has associated value **1**. (By Ropes over Pulley rule, which says that if a pulley system has two ropes over it, and we know the value of one rope, the value of the other rope is the same.)

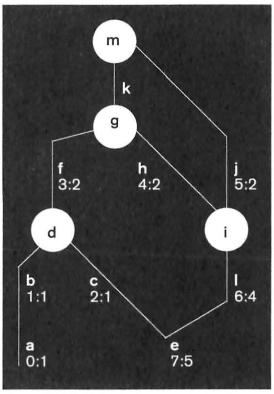
3

The rope at **c** (value **1**) is in the pulley-system of **d** which hangs from the thing at **f** which is a rope. The pulley-system at **d** also contains the thing at **b** which is a rope with value **1**. . . Attention is now at **f**.

4

The rope at **f** (value **2**) is the pulley system at **g**. . .

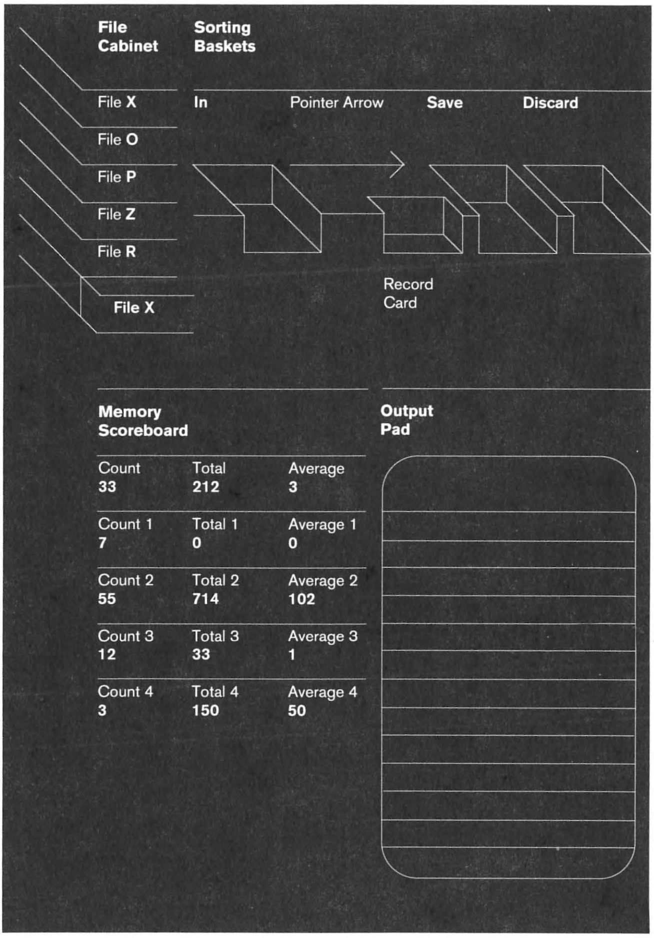




Adapted with permission from Larkin, J. H., & Simon, H. A. 1987. Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11, 65-99.

Figure 4 A model for understanding a data base.

(Mayer Fig. 7.) A model for understanding data base programming. Students can follow the program as it moves from one element to the next by following through the images.



Adapted with permission from Mayer, R. E. 1976b. Some conditions of meaningful learning for computer programming: Advance organizers and subject control of frame order. *Journal of Educational Psychology*, 68, 143-150.

Figure 5 Constrasting verbal and visual presentations of a geometry problem.

Adapted with permission from Larkin, J. H., & Simon, H. A. 1987. Why a diagram is (some-times) worth ten thousand words. *Cognitive Science*, 11, 65-99.

Verbal Statement of Problem:

1
Two transversals intersect two parallel lines and intersect with each other at a point X between the two parallel lines.
2
One of the transversals bisects the segment of the other that is between the two parallel lines.
3
Prove that the two triangles formed by the transversals are congruent.

The diagram makes explicit the points, segments, angles and triangles implied in the verbal statement of the problem.

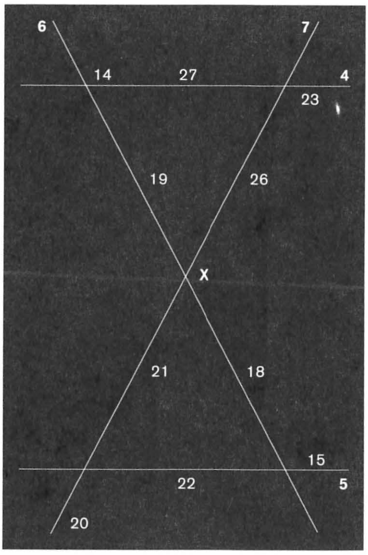


Figure 6 The mutilated checkerboard with and without contrast versus a verbal description.

Adapted with permission from Kaplan, C. A., & Simon, H. A. 1990. In search of insight. *Cognitive Psychology*, 22, 374-419.

Verbal description:

Consider a standard 8 x 8 checkerboard, two of whose diagonally opposite corners have been removed. Imagine placing dominos on the board so that one domino covers two horizontally or vertically (but not diagonally) adjacent squares. The problem is either to show how 31 dominos would cover the 62 remaining squares, or to prove logically that a complete covering is impossible.

The solution requires representing the problem as one of parity between the black and white squares. Once the problem solver notices that there are two fewer white squares than black, it becomes apparent that a complete covering is impossible.

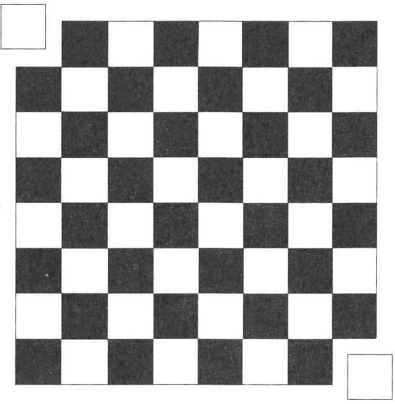


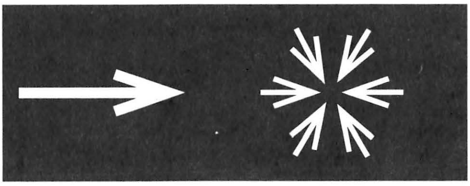
Figure 7 **Contrasting diagrams developed to help individuals solve a problem.**

Adapted with permission from Gick, M. L., and Holyoak, K. J. 1983. Schema induction and analogical transfer. *Cognitive Psychology*, 15, 1-38; and with permission from Beveridge, M., and Parkins, E. 1987. Visual representation in analogical problem solving. *Memory & Cognition*, 15, 230-237.

The problem:

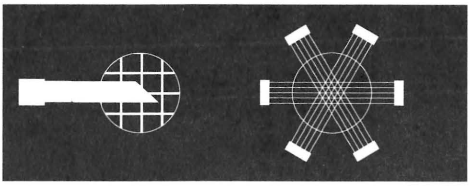
Suppose you are a doctor faced with a patient who has a malignant tumor in his stomach. It is impossible to operate on the patient, but unless the tumor is destroyed the patient will die. There is a kind of ray that can be used to destroy the tumor. If the rays reach it all at once at a sufficiently high intensity, the tumor will be destroyed. Unfortunately, at this intensity the healthy tissue that the rays pass through on the way to the tumor will also be destroyed. At lower intensities the rays are harmless to healthy tissue, but they will not affect the tumor either. What type of procedure might be used to destroy the tumor with the rays, and at the same time avoid destroying the healthy tissue?

Figure 7.1



Unsuccessful diagram representing the dispersion solution used by Gick and Holyoak. It represents the necessity to break one large X-ray into a number of small X-rays all pointing to the tumor, but it does not represent the differential intensity between the single large X-ray and the many small X-rays.

Figure 7.2



Successful diagram used by Beveridge and Parkins. It not only represents the difference in the number of X-rays, but it shows the essence of the solution – that the many small X-rays are less intense, but then combine their intensities at the site of the tumor.

Figure 9 **Four representations of a problem to be programmed.**

Adapted with permission from Mayer, R.E.1976a. Comprehension as affected by the structure of problem representation. *Memory & Cognition*, 4, 249-255.

Verbal and diagrammatic forms of four different structures were presented. The most successful was the Example structure regardless of whether it was presented verbally or visually.

9.1 **Jump**

Verbal

1 If **Indiana** defeats **Michigan** go on to next step, otherwise go to step **7**.

2 If **Ohio** defeats **Michigan** go on to next step, otherwise go to step **6**.

3 If **Indiana** defeats **Ohio** go on to next step, otherwise go to step **5**.

4 You win prize **F**.

5 You win prize **E**.

6 You win prize **D**.

7 If **Ohio** defeats **Michigan** go on to next step, otherwise go to step **9**.

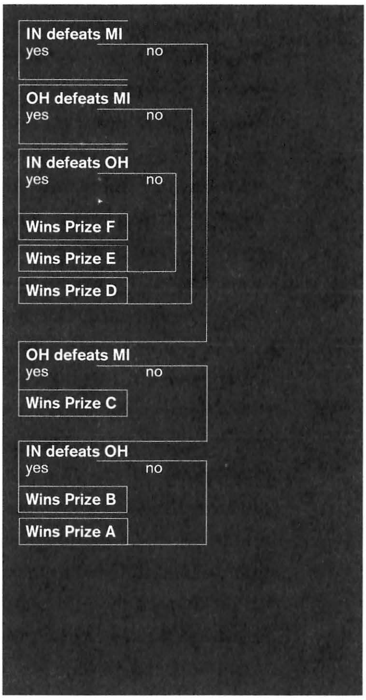
8 You win prize **C**.

9 If **Indiana** defeats **Ohio** go on to next step, otherwise go to step **11**.

10 You win prize **B**.

11 You win prize **A**.

Diagram (Flow)



72
Mayer, 1976a, previously cited at 60.

73
Mayer, 1989, previously cited at 58.

Figure 8 Contrasting verbal and visual versions of a math problem.

Adapted with permission from Moyer, J. C., Sowder, L., Threadgill-Sowder, J., and Moyer, M. B. 1984. Story problem formats: Drawn versus verbal versus telegraphic. *Journal for Research in Mathematics Education*, 15, 342-351.

Figure 8.1 **Verbal description:**

There are 6 boxes of crayons. There are 24 crayons in each box. Each box costs 90 cents. How much do the 6 boxes cost?

Note that the picture gives all the information in an ordered – and simultaneous – form. Thus all the problem solver needs to do is to figure out which are the relevant quantities and what operation to apply.

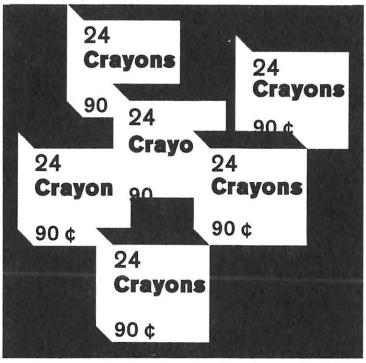
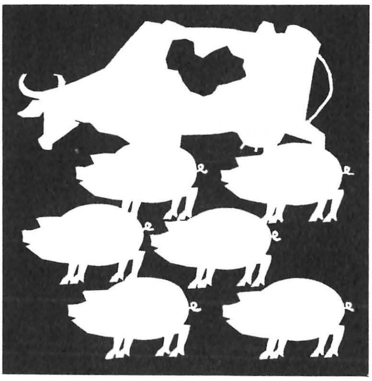


Figure 8.2 **Verbal description:**

Farmer Smith has 6 pigs for every cow. Let **P** stand for the number of pigs and **C** stand for the number of cows. Write an equation relating the number of pigs to the number of cows...

Try to use the visual to solve the problem. Does it help? It doesn't help most students, probably because the "trick" to the problem is to understand how ratios and algebraic symbolization work, not to understand the relative quantities.



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Mayer, R.E., 1976b. Some conditions of meaningful learning for computer programming: Advance organizers and subject control of frame order. *Journal of Educational Psychology*, 68, 143-150; and Mayer, R.E. and B.K. Bromage. 1980. Different recall protocols for technical texts due to advance organizers. *Journal of Educational Psychology*, 72, 209-225.

66
For example, see Polich, J.M. and S.H. Schwartz. 1974. The effect of problem size on representation in deductive reasoning. *Memory & Cognition*, 30, 683-686. Schwartz, S.H. 1971. Modes of representation and problem solving: Well evolved is half solved. *Journal of Experimental Psychology*, 91, 347-350.

67
Beveridge, M. and E. Parkins, 1987, previously cited at 59.

68
Gick, M.L. and K.J. Holyoak, 1980, previously cited at 60.

69
Duncker, K. 1945. On problem solving. *Psychological Monographs*, 58 (5, Whole No. 270).

70
Moyer, Sowder, Threadgill-Sowder et al., 1984, previously cited at 59. Threadgill-Sowder, J., L. Sowder, J.C. Moyer and M.B. Moyer. 1985. Cognitive variables and performance on mathematical story problems. *Journal of Experimental Education*, 54, 56-62.

71
Kulm, Lewis et al., 1974; and Sims-Knight and Kaput, 1983; both previously cited at 60.

in which the problem can be solved by going from place to place in the diagram. To solve the problem using only the verbal description of the problem, one has to read repeatedly through the problem to find the next step. In other words, the visual diagram has structured the problem into local regions that represent steps in the problem.

Organizational and interpretational diagrams also facilitate search in noncomputational domains, such as understanding the steps through a biological or chemical cycle, or moving through a computer program. For example, Mayer[65] created a model for understanding data base programming that included pictures of a file cabinet, sorting baskets, memory scoreboard, and output pad (*see figure 4*). A data base program moves from one to another of these elements. Thus, students can follow the program through by moving from one picture to the next – the visual image may help them hold the concept in mind. Two-dimensional matrices that systematically record the values of variables (numerical or otherwise) also facilitate searches for communalities, relations, missing cells, etc.[66]

Making the implicit explicit. The second circumstance in which Larkin and Simon identify superiority for visual diagrams is when the visual representation makes explicit crucial aspects of a problem that are implicit in the verbal representation. They give the example of a geometry problem (*see figure 5*) in which the points, segments, angles and triangles are not mentioned specifically in the verbal description, but are made explicit in the drawing. In Kaplan and Simon's 1990 paper, they explored a problem called the mutilated checkerboard problem in which a picture of the checkerboard made explicit that there were black and white squares where such information was only implicit in a verbal description of the mutilated checkerboard. The patterning of black and white gave the clue to the solution (*see figure 6*).

Larkin and Simon's second factor – that visual representations sometimes make crucial elements of the problem representation explicit has been supported in several quite different contexts. Beveridge and Parkins[67] improved on a graphic developed by Gick and Holyoak[68] (*see figure 7.1*) that had failed to help individuals solve the radiation problem developed by Duncker.[69] The difference between their figures and those of Gick and Holyoak was that theirs (*figure 7.2*) made explicit that the small, less intense rays would combine at the site of the tumor to become sufficiently intense to destroy the tumor. Thus only figure 7.2 makes explicit the crux of the problem, which is only implicit in the verbal problem.

Studies of visuals in mathematical problem solving also suggest that only visuals that represent the essential components of the solution will facilitate finding the answer. Pictures have been found to facilitate solving arithmetic problems, particularly for low readers,[70] whereas they have been found to provide little help with algebraic story problems.[71] In the studies of arithmetic problems (*see figure 8.1*) they facilitate because they show both the quantities and the relations among the quantities, which is what one needs to know to solve the arithmetic problem. In algebraic story problems the pictures capture the arithmetic representation of the problem (*see figure 8.2*) but do not help the student translate that quantitative representation into the algebraic symbol system. In support of this interpretation, Kulm et al. found that the picture helped students remember the words in the problem and helped them draw a sketch (create the representation given by the problem), but it did not help them create the solution representation necessary to solving the problem. Thus, such visuals, like the one developed by Gick and Holyoak in their 1980 and 1983 studies, fail to capture the essence of the solution.

A third example of the facilitative effect of making the implicit essence of a problem explicit is a study by Mayer[72] that also demonstrated that the best representation is not always the pictorial diagram. The problem was a logical one – there was a three-team tournament with six prizes obtained for various outcomes of the tournament. The subjects had to answer eight questions that gave either antecedents or consequences and asked for possible deductions (e.g., If team 1 defeats team 2, then could you possibly win prize X? If you won prize X, which is the best team?). Mayer devised four different problem representations and implemented them either verbally or pictorially (*see figure 9*). Two representations – Jump and Short-Jump – were a series of if-then propositions with the outcomes specified as GO-TO steps (the only difference between them was that Jump had eleven steps with intermixed "You win prize X" and "Who defeats whom?" statements, and Short-Jump integrated the eleven steps into five steps with both possible outcomes declared in each step). Mayer's third structure used if ... then ... else propositions structured into an indented, more integrated form. The fourth representation (called Example) was a contingency table that set up an advance organizer of all three games and then in each of six steps listed all possible winners; the diagram version was set up like a tournament sheet with alternative outcomes. There were clear differences in performance among the eight conditions (range of performance was 51 percent correct to 82 percent correct in the first experiment and 70 to 96 percent in the second experiment). There was, however, no clear superiority of diagrams over the verbal representations. In fact, in both experiments the best performance was the verbal version of Example, which made clearest the logical relations necessary to answer the questions.

Diagrams as organizational structures. Mayer, in a review of twenty studies involving thirty-one separate tests,[73] has also addressed the issue of the relation between visuals and problem solving. This research involved organizational and interpretational diagrams (*see figure 1*) in science and computer education and the subjects were tested on what they remembered (exact or verbatim memory), what they understood (conceptual memory) and whether they could apply what they learned to solve problems (problem-solving). The diagrams were consistently effective in facilitating conceptual memory and problem solving, but interfered with verbatim recall. This pattern of results is consistent with

9.2 Nest

Verbal | **Diagram** (Flow)

If **Indiana** defeats **Michigan** then

If **Ohio** defeats **Michigan** then

If **Indiana** defeats **Ohio** then
you win prize **F**.

Otherwise you win prize **E**.

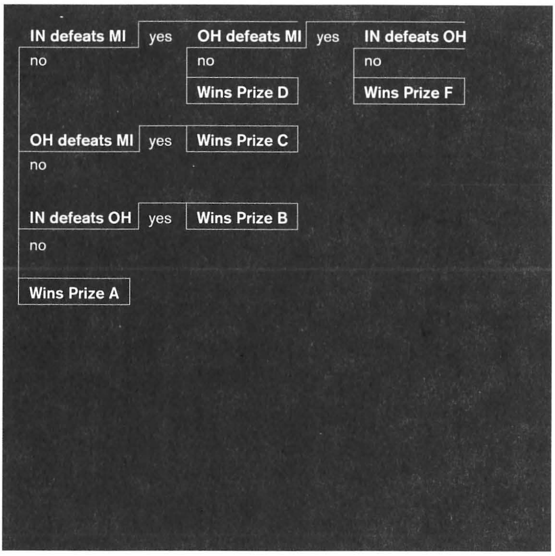
Otherwise you win prize **D**.

Otherwise
If **Ohio** defeats **Michigan**
then you win prize **C**.

Otherwise
If **Ohio** defeats **Michigan**
then you win prize **C**.

Otherwise,
If **Indiana** defeats **Ohio**
then you win prize **B**.

Otherwise
you win prize **B**.



9.3 Short-Jump

Verbal | **Diagram** (Flow)

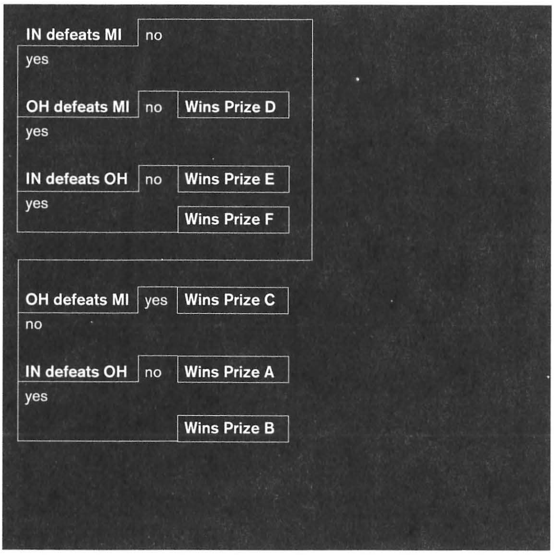
1 If **Indiana** defeats **Michigan**
go on to step **2**,
otherwise go to step **4**.

2 If **Ohio** defeats **Michigan**
go on to step **3**,
otherwise you win prize **D**.

3 If **Indiana** defeats **Ohio**
you win prize **F**,
otherwise you win prize **E**.

4 If **Ohio** defeats **Michigan**
you win prize **D**,
otherwise go to step **5**.

5 If **Indiana** defeats **Ohio**
you win prize **B**,
otherwise you win prize **E**.



9.4 Example

Verbal

Diagram (Flow)

There are three games:

1 **Indiana** vs. **Michigan**,
2 **Ohio** vs. **Michigan**, 3 **Indiana** vs.**Ohio.**

If the winners are
1 **Indiana**, 2 **Ohio**, 3 **Indiana**,
then you can win prize **F**.

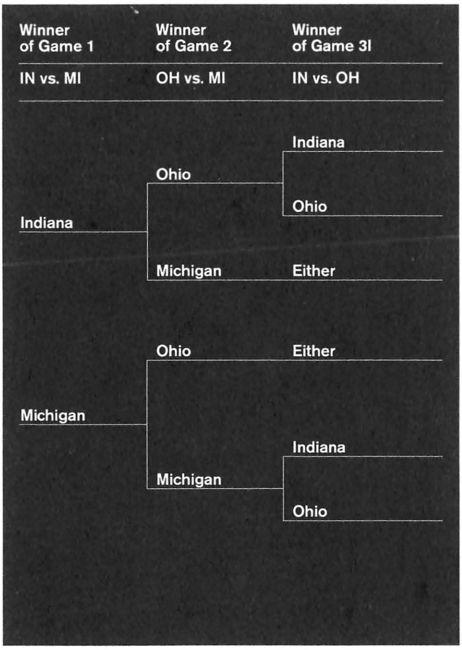
If the winners are
1 **Indiana**, 2 **Ohio**, 3 **Ohio**,
then you can win prize **E**.

If the winners are
1 **Indiana**, 2 **Michigan**, 3 **either team**,
then you can win prize **D**.

If the winners are
1 **Michigan**, 2 **Ohio**, 3 **either team**,
then you can win prize **C**.

If the winners are
1 **Michigan**, 2 **Michigan**, 3 **Indiana**,
then you can win prize **B**.

If the winners are
1 **Michigan**, 2 **Michigan**, 3 **Ohio**,
then you can win prize **A**.



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Levin, Anglin and Carney, 1987, previously cited at 54.

75
Kieras and Bovair, 1984, previously cited at 57.

76
Holliday, W.G., L.L. Brunner and E.L. Donais. 1977. Differential cognitive and affective responses to flow diagrams in science. *Journal of Research in Science Teaching*, 14, 129-138.
Kulhavy, R.W., N.H. Schwartz and S.H. Shaha. 1983. Spatial representation of maps. *American Journal of Psychology*, 96, 337-351.
Taylor and Thompson, 1982, previously cited in 14.
Winn, W.D. 1981. The effect of attribute highlighting and spatial organization on identification and classification. *Journal of Research in Science Teaching*, 18, 23-32.
Winn, W.D. 1982. The role of diagrammatic representation in learning sequences, identification and classification as a function of verbal and spatial ability. *Journal of Research in Science Teaching*, 19, 79-89.

the explanation that the visuals help students create a conceptual model and reorganize what they have read to fit that model. Insofar as the model is effective, it should – and does – help students understand the material and use the material to solve problems. Because the visuals encourage reorganization of the textual material, students in such conditions would be expected to show worse straight recall.

What is it about Mayer's visual models that makes them effective? Simon's two principles are certainly involved – Mayer's visual models often do organize students' search through elements of a concept and they do make explicit that which is implicit in the text (e.g., showing sparse versus dense dispersion of molecules as differing numbers of circles with downward pointing arrows in same-sized containers to show the difference in gravitational pull). Some of his diagrams, however, derive their power from their organizing and integrating nature; that is, they abstract the essential properties from the text, organize them, and show the relations among the concepts. The spatial layout characteristics of a visual permit those elements and their relations to be represented simultaneously – something text can never do. This integrative function is, of course, making the organization of a topic explicit, so it may not be different than Simon's second principle, particularly since the current state of research has not shown that it operates independent of the explicit visual/implicit textual principle. It may be, for example, that the capacity of the visual diagram to denote the conceptual structure of a topic (i.e., the parts and their relation to the whole) may still facilitate relative to text, even when the text explicitly describes that structure.

Noninformational aspects of visuals

Research on the effectiveness of visuals has demonstrated clearly that visuals that clarify text promote learning. Does that mean that the only differences among visuals that affect their effectiveness is their informational content? If so, their aesthetic values, their vividness, their concreteness would be irrelevant. There is little research exploring these issues, but what is available suggests that other variables are largely irrelevant.

The research described earlier found that pictures that serve only a decorative function do not facilitate memory.[74] Nonetheless, it might be that visuals that have both informational content and are vivid or aesthetically pleasing might be more memorable than those with the same informational content but dull, unappealing presentation. There are remarkably few studies that address this issue in any way and the few that have done so have not provided strong support for a vividness effect. Kieras and Bovair[75] compared two models of an electronic device. One was incorporated into a Star Trek fantasy – certainly vivid – whereas the other was a straightforward technical diagram. There was no difference in effectiveness. Several studies have compared diagrams with elements identified by words (dull) or pictures (vivid), but the findings have been inconsistent.[76] Moreover, the pictures may have served an informational role in some of these studies (e.g., drawings of dinosaurs

77
Tufte, 1983, previously cited in 5.

78
For discussion of other principles, see Levie, W.H. 1987, previously cited in 55; Levin et al., 1987, Research on pictures: A guide to theliterature. In D.M. Willows and H.A. Houghton, eds. *The Psychology of Illustration* (volume 1, Basic Research). New York: Springer-Verlag, 1-50, previously cited in 54. Readence, J.E. and D.W. Moore. 1981. A meta-analysis of the effect of adjunct pictures on reading comprehension. *Psychology in the Schools*, 18, 218-224. See also Rusted, 1984, previously cited in 53; and Winn, 1987, previously cited in 6.

that cued the direction of the evolutionary sequence). Related to this point, attempts to make graphs and diagrams more aesthetically pleasing or more eyecatching often result in less effective or even misleading graphics.[77]

Thus, the importance of aesthetic or attention-getting properties of visuals is largely unexplored, but the available evidence suggests that, so long as the informational content is attended to, even dull or unappealing visuals will be effective in their educational function.

Practical implications of scientific studies of visuals with text

The research reviewed above, when considered as an integrated whole, suggests three principles for designers.

Principle 1:

One Picture Is Not Always Worth More Than 10,000 Words

It is a mistake to assume that, just because visuals often help learners to remember and understand information and to solve problems, that visual presentation is always effective. In general we can conclude that visuals will not help or will actually interfere with learning in the following circumstances:

- when pictures are merely decorative
- when the essence of the problem is made as clear or clearer by a verbal presentation than by a visual presentation
- when visuals fail to elucidate the phenomenon, as explicated in Principle 2.

This list of circumstances in which visuals do not facilitate learning is not meant to be exhaustive, but rather to illustrate that such circumstances exist.[78]

Principle 2:

Designers' Primary Consideration Should be to Produce a Representation That Elucidates the Phenomenon

The clearest conclusion from this research is that visuals facilitate learning and problem solving if they help readers make sense of the material. Three ways in which visuals can do this have been identified:

- when the visual helps learners search through multifaceted information
- when the visual makes explicit crucial features of the solution that is implicit in the text
- when the visual organizes and integrates complex information. In addition, visuals facilitate memory if they represent the text adequately even if they do not fulfill one of the above criteria.

To make visuals that meet this principle will require that designers' creativity be grounded firmly in an understanding of the content of the material.

79
Gould, J.D., S.J. Boies, S. Levy, J.T. Richards and J. Schoonard. 1987. The 1984 Olympic Messaging System: A test of behavioral principles of system design. *Communications of the Association for Computing Machinery*, 30, 758-769.

Principle 3:
Features Not in the Service of the Informational Content
Must be Used with Care

The research does not give clear guidance about how to make informational graphics decorative and attention-getting, but it does make it clear that purely decorative pictures will not facilitate textual learning. There apparently is a danger that decorative and attention-getting elements may make a visual less informative. A safer approach would be for designers to put their creativity into producing the best representation of the crucial informational content.

User-based Design

Clearly, when scientific research yields clear, consistent results, they can be used as guidelines for effective design. Nonetheless, as the previous section indicated, designers will often find themselves in situations in which the well-established scientific principles are not sufficient or applicable. In those instances, user-based design is the only answer.

User-based design starts with the premise that designs should be maximally effective for the users of the design. It accepts the limitations of our impressionistic reasoning and insists that users' cognitions and needs be incorporated from the beginning of the design process. This is typically done by creating "quick and dirty" scenarios, models or prototypes for the user to try rather than implementing the entire project and then testing its effectiveness. If the results are disappointing, changes can be made, a new prototype developed and tested before the time, effort and expense is put into the implementation of the entire project. The steps of redesign and testing can be repeated as often as needed. Implementation of the design is postponed as long as possible, because errors can be corrected more easily while still in prototype.

A nice example of user-based design in computer software development incorporated early focus on users and tasks, empirical measurement and iterative design into the design of the multilingual Olympic Messaging System (OMS) used at the 1984 Olympic Games in Los Angeles.[79] The OMS allowed Olympians (the main user group) to send and receive voice messages among themselves and to and from their family, friends, former coaches, etc. throughout the world. The design team started by developing written scenarios of simulated "conversations" on the proposed system – their first prototype – and gave them to people to comment upon. Users could understand the functions of the system because they saw their behavioral consequences. It also allowed users' input at a time when their comments could influence the design and before any programming was done. They found that many of the functions that the designers thought crucial were unimportant to users. In the same way, the design team tried out drafts of user guides before finalization – their second prototype. This also brought the system to potential users in a

80
For technical documentation, see Carroll, J.M., P.L. Smith-Kerker, J.R. Ford, and S.A. Mazur-Rimetz. 1988. The minimal manual. *Human-Computer Interaction*, 3, 123-153.

For product design, see Powell, E.N. 1989. *Designing for product success: Essays and case studies from the TRIAD design project exhibit.* Boston, Massachusetts: Design Management Institute.

Also Mantei, M.M. and T.J. Teorey. 1988. Cost/benefit analysis for incorporating human factors in the software lifecycle. *Communication of the Association for Computing Machinery*, 31, 428-439.

form that facilitated users' responses. It took two hundred iterations of the English version of the guide to produce the final version, which shows you how unanticipated the needs and issues of the audience can be. This "try-it" approach was used at every step of the development process – they simulated the push-button telephone keys, the interactions between user and system, and the kiosk in which the system was to be placed. After the working prototype was developed, it was subjected to a number of tests with about one hundred participants, which identified bugs, additional types of help needed, etc. Finally, they ran "try-to-destroy-it" tests plus several kinds of field tests with ten computer science students from a local college.

That the steps taken by the OMS designers were successful is demonstrated by two facts. First, the final form of the design was not anticipated by designers. Users did not want functions designers thought critical and designers' vision of an easy-to-use system was too difficult for the users. Second, the resulting system was unusually successful – forty percent of the Olympians used it at least once, and it was used an average of one to two times per minute, twenty-four hours per day, a record use of electronic mail by noncomputer users.

Although this example described the development of a software product, the same principles have been used in technical documentation and product design.[80] Clearly, the techniques are widely adaptable. As an example of how it would work in producing graphics, consider the DC subway signage project. If user-based design had been used in the DC subway project, prototypes of the signage would have been presented to users for brief periods of time (equaling the amount of time the average rider would have as her train passed through a station) and the users would have been asked to read the signs. The users' inability to read the signs would have been obvious. (Of course, we are dealing from hindsight here and so know exactly what to test to uncover the error. In the normal circumstance the designers would probably have had to discover the reading problem while testing scenarios.)

Principles

Prototyping, Iterativeness, and Postponement of Implementation

The essence of the prototype model is to create preliminary versions of the product to try before deciding on a final design. In the OMS project the prototypes included behavioral scenarios of how the system would work, the manuals, the keypad interactions and the kiosk. Notice that it often takes some imagination to develop these prototypes. Each prototype was tested and changes incorporated into a subsequent prototype, which was in turn tested. A working prototype was not created until the simulated prototypes had answered all the questions the designers and users could generate. The working prototype was also tested and changed as a result of that testing. Only after all aspects of the design had been

Continued from page 348.

39 million 999,999 Years

365 days
22 hours 40 minutes

One of the things
we looked at
was the planet Jupiter.
Huge by Earth standards,
it is still
a tiny fraction the size
of a star.
But it is an impressive object
in a small telescope,
and as we looked at its four bright moons
and bands on its surface,
our Kamikaze Photon
passed its orbit.

39 million 999,999 Years

365 days
22 hours 59 minutes

My friends went home,
I closed up the big telescope,
and settled down in my star chair.

Continued on page 378.

81
Powell, 1989, just cited.

82
Shriver, K.A. 1989. Document design from 1980 to 1989: Challenges that remain. *Technical Communication*, Fourth Quarter, 316-331; and Wright, P. 1989. Can research assist technical communication? *Proceedings of the 1989 International Technical Communication Conference (RT3-RT6).* Washington, D.C.: Society of Technical Communication.

tested by appropriate user groups did they actually implement their design and systematically test it.

User-based design is often criticized as too expensive. Its proponents, however, claim just the opposite. Their claim to economy is twofold. First, by creating prototypes and incorporating user testing from the first to last prototype, many errors can be detected and corrected before implementation; consequently fewer errors need be corrected after manufacturing has begun, development cost is lower and, often, development time is shortened.[81] Second, the resulting product is more usable and thus often is preferred by customers.

Exploration of users' behaviors and thoughts

In a user-based design strategy one finds out whether one's design is communicating by presenting prototypes to users. Note that in this strategy the designers do not describe their ideas and ask users whether they think a proposed design will work. Rather the designers present a concrete example of the product and have users use it (or at least put themselves in the role of using it). In the OMS example, they did not simply ask the users which of a list of functions the users wanted (which often does not work because users can't always understand what the designer is asking). Rather, they presented users with scenarios, which allowed users to experience the interface behaviorally.

User-based design is not equivalent to considering one's audience, because in the former designers actually interact with users and in the latter, they intuit what the audience is like. People's intuitions are informed and distorted by our impressionistic reasoning biases discussed earlier. Therefore, it should not be surprising that considering one's audience has been found to be inadequate.[82] Nor is user-based design equivalent to market research, which typically surveys people's needs and desires and is thereby limited to their conscious desires, based on their limited previous experiences and on their limited ability to understand the lingo of an unfamiliar area. Market research may sometimes be a useful adjunct to user-based design, but its goal – to find out what will sell – encourages a focus on easily advertisable functions rather than on ways to make a product truly more usable. Thus, to continue the software example, market research would determine whether a messaging system was desirable and would likely result in a long list of desired functions and a recommendation that it be user friendly. In contrast to user-based design, it would not yield the information that the system became usable for its naive users only when functionality was reduced to a bare minimum (e.g., the final version had no way the sender could find out if the message arrived and no way for the sender to insert text if s/he had forgotten something s/he wanted to say, both of which are standard features in many electronic mail systems).

User-based design encourages innovativeness in user-oriented features in two ways. First, observing and interacting with users working with prototypes teaches the designer how users think about – and misunderstand and get confused by – both the form and the content of

Continued from page 376.

40 million years

And then it happened.
Forty million years,
untold trillions of miles,
came to an end in a single instant.
I pointed the aluminum tube
in the direction of the Sombrero galaxy;
I looked through the eyepiece.
Five hundred millimeters from my eye
the photon passed
through the beautifully curved glass lens
which changed
the final millimeters of its course
so that it passed
through the eyepiece
and into my eye.
There it collided
with a rod changing my chemistry.
The photon was destroyed.
Its mission complete.
The chemical changes
it generated in my eye caused
a small electrical impulse
to go to my brain,
and as that impulse combined
with many similar impulses
from many similar photons
which had also traveled
for 40 million years,
I breathed a sigh and thought,
"There it is.
That little blur of light
is the Sombrero Galaxy."

Continued on page 380.

the design. Second, designers are likely to dismiss their creative ideas for designs for fear that they would not be effective. In user-based design it is easy to get an idea of how such ideas might work by presenting them informally and it is possible to develop such ideas through iterative testing.

Thus, user-based design provides input concerning users in two ways that no other part of design can do. First, it solves the communication problem between designer and user by setting up situations in which users can provide behavioral evidence of their functioning within the system. No designer intuition, user survey or interview can do that. Second, it provides a unique opportunity for designers to come to understand the cognitive processes of others and to create innovative solutions to users' problems.

How user-based design controls impressionistic reasoning

The example of the development of OMS demonstrates ways in which user-based design decreases reasoning errors:

- The designers did not rely on their own experiences or on the accounts of the experiences of a few colleagues or friends. They collected systematic data from a broad spectrum of people, ranging from the naive eventual users to experts.
- They did not rely on their own expert opinion about the desirable characteristics of a messaging system, but rather tested users at each step of the design development.
- At critical steps substantial numbers of users were tested (and presumably their data considered as a whole). Thus, the designers could consider group data statistically rather than having to rely on multiple case studies.

These characteristics provide the opportunity for designers to control their impressionistic reasoning biases. By testing a variety of users in different ways, designers can create the conditions identified as effective at curbing biases. They can

a *provide for themselves consistent and specific feedback,*
b *think through alternative explanations for their particular design hypotheses and create some feedback for them and*
c *search for a complete picture of the situation by testing a variety of users on a variety of tasks.*

Note, however, that collecting these kinds of information is not inevitable in user-based design. Designers must consciously incorporate these into the process.

User-based Design versus Scientific Inquiry

It is important to understand that user-based design differs from traditional scientific research in many important ways beyond the obvious one of being done in the field. Designers have neither the time nor financial resources to test rigorously every aspect of their design, because the goal of user-based design is to solve design problems for the particu-

Continued from page page 378.

Conclusion

Writing this all seems so pitifully inadequate to me.

I'm sure there will be physicists and astronomers out there who feel I have taken too much liberty with quantum mechanics as they now understand it when I speak of this journey as if we really could track a single photon and see it pass the objects mentioned. I trust they will allow for a certain amount of poetic license.

What I've tried to convey in the best way I know how is a perspective on time and distance. But in the final analysis, I know I have only scratched the surface. I cannot even adequately convey those things I think I know, and I certainly do not claim to know how far 40 million light years is.

How in the world can I know it? There is nothing in my experience to which I can compare it.

And that is the real message I want to communicate. I want to convey the incredible difficulty in even beginning to show someone the world that modern science is revealing. It is a world strange beyond belief and yet I think we all – scientists and non-scientists alike – are truly ignorant of it.

We're attempting to describe the indescribable. We kid ourselves by inventing words, such as infinity, eternity, light year, parsec, and mathematical notations, such as 10-to-the-23rd. These allow us to gather some sort of picture of the new reality. They roll off our tongues glibly.

And all the nice little analogies that the scientists and the science writers come up with can only nudge us in the direction of this reality; but they leave us so far short of it, it is pitiful.

And there are some things perhaps better left unsaid. Relativity theory, for example, tells us that from our perspective, that photon has been journeying for 40 million years. From the photon's perspective, it has been traveling at the speed of light and at that speed no time has passed. It is all one in the same instant. I have been journeying these 40 million years, and at last the atoms that currently make up me (I'm not sure if they're the same ones that were me on July 9, 1941) – these atoms have at last crossed the path of that photon which was here and at the Sombrero Galaxy all in the same instant.

It is mind boggling, of course. And in studying these things, I find that I renew a delightful sense of child-like wonder.

Albert Einstein once said:

> **"I want to know**
> **how God created this world.**
> **I am not interested in this**
> **or that phenomenon,**
> **in the spectrum of this**
> **or that element.**
> **I want to know His thoughts;**
> **the rest are details."**

What lovely arrogance!

83
Gould et al., 1987, 762, cited in 79.

84
Ericsson, K.A. and H.A. Simon. 1984. *Protocol Analysis: Verbal Reports as Data.* Cambridge, Massachusetts: The MIT Press.

lar project. That typically means that the experimental control necessary for the establishment of a scientific principle is not used. For example, Gould et al. found that four audio alternatives on an audio prompt was too many (e.g., "press 1, listen again; 2, listen to another new message; 3, send a message; 4, hang up.").[83] In their next prototype they reduced the alternatives to three, but they undoubtedly made other changes as well. Their subsequent version worked better (fewer problems, more satisfaction) than the previous one and that was sufficient for their purposes. If this had been a scientific inquiry, it would have been necessary to isolate the change in the number of possible options from other changes and to test the two versions systematically – with a substantial sized sample, statistical analyses, etc. What such a scientific inquiry permits that is impossible in the user-based design is the conclusion that one should not use more than three alternatives in a voice-messaging system. The danger in user-based design is that the designers may remember that principle as substantiated and use it blindly in their next design. This would be an error – the appropriate response would be to keep it on the list of things to be checked out in user testing in the next design, because the three-principle may have been a fluke of this particular situation.

In addition, the less rigorous qualitative techniques typical of protocol analysis are usually more appropriate to user-based design.[84] That means that many of the important controls of scientific research – appropriate and extensive sampling, experimental controls and statistical analyses – are not used.

Thus, it is crucial in user-based design that designers understand that the principles they discover in the development of a particular design are more tenuous than is true in scientific inquiry. They have not tested the influence of any one principle independent of other principles, they often have not tested enough users to have a scientifically valid sample, they have usually not tested statistically the effect of that principle, and they have certainly not tested the generality of the principle (by testing in different laboratories with different investigators and different content material, etc.).

While user-based design helps designers to overcome the biases of their impressionistic reasoning relative to no testing, it still allows impressionistic reasoning biases – the tendency to form strong beliefs on little evidence, the tendency to settle on the first hypothesis without considering alternatives, the tendency to look for confirmatory data and ignore disconfirmatory evidence, the failure to obtain or consider, when available, all the evidence or evidence from all the subjects.

This discussion should make it clear that user-based design can not replace scientific research. The development of scientifically valid general guidelines can help to narrow the range of possible prototypes. Furthermore, the more one understands about the perceptual and cognitive processing of humans, the better one's intuitions about effective ways to communicate are likely to be and the better one's initial prototypes will be. Finally, empirically-based guidelines, in the hands of

85
Clark, K. and T. Fujimoto. 1989. Overlapping problem solving and product development. In K. Ferdows, ed. *Managing International Manufacturing.* Amsterdam: Elsevier. See also Powell, 1989, cited in 80.

86
Gould et al., 1987, cited in 79.

87
Duffy, T.M., T. Post and G. Smith. 1987, May. An analysis of the process of developing military technical manuals. *Journal of the Society for Technical Communication,* 34, 70-78.

88
Sherwood, B.A. and J.H. Larkin. 1989, Spring. New tools for courseware production. *Journal of Computing in Higher Education,* 1, 3-20.

a designer who understands his own human biases and limitations, can help him or her to correct those biases.

Personnel issues in user-based design projects

User-based design requires that one unit maintains control over all aspects of the design. In the development of the OMS the design team developed all aspects of the project, the kiosk, the audio system, the computer implementation and the user documentation. In a traditional management scheme, a product is handed off from one department to another in a linear fashion, which discourages the use of iterative design and often results in less effective products.[85] Gould et al. pointed out that they would never have been able to rewrite the manual two hundred times if they had had to negotiate with another department.[86]

The use of a team approach can be very effective in many settings. For example, in the development of textbooks, the authors and designers need to work together from the start of the project. Much of the user feedback will apply to both text and visuals and iterating both together will likely build a stronger product. An alternative approach is to teach skills required in the user-based orientation to the expert, as Duffy, Post and Smith[87] argue with respect to documentation and Sherwood and Larkin[88] argue in reference to interactive computer software. It seems likely that both strategies can be effective. Specifically, I would predict that two variables determine whether a team or single designer approach will work better. Team design apparently works better in situations in which the necessary expertise is too wide to be held by one person, e.g., in complex manufacturing situations, and in situations in which group problem solving is particularly advantageous, e.g., in situations in which different perspectives may interact synergistically. Development of solutions by the individual designer will be effective when those conditions do not obtain, but only if the designer has the necessary array of expertise – s/he must understand the subject matter domain and user-based testing as well as design.

Summary

The problem addressed in this paper is how to ensure that visual representations will effectively communicate to their intended audience. Designs and design principles developed by expert designers sometimes promote effective communication and sometimes do not. Because presumably designers want their designs to communicate effectively, the failure must be one of judgment. A perusal of the psychological research on judgment makes it clear that the problem lies in the way humans typically reason when they make judgments. This research can be summarized by the following comparison:

When forming one's initial hypothesis:

- People *should* consider all possible positions, using all available information

- People *do* rapidly form initial impressions, based primarily on
  - a *their own personal experiences and those of one or a few individual cases (even when statistical data are available),*
  - b *the opinion of experts and*
  - c *whatever is salient, motivated, recent or expected.*

After one's initial hypothesis is formed

- People *should* consider systematically all information available, not just that which confirms their hypotheses. Special attention should be paid to finding disconfirmatory data and exploring alternative explanations. The most convincing evidence is statistical – similar information gathered on a large number of people.
- People *do* try to conserve their first impression by seeking only confirmatory evidence and by overevaluating that evidence. They ignore statistical data whenever any alternative is available.

Controlling these judgmental biases is not just a matter of becoming aware of the problem. Effective techniques for curbing biases are

- a *seeking and evaluating consistent and specific feedback,*
- b *explicitly working at debunking one's beliefs by searching for disconfirming evidence or alternative interpretations and*
- c *searching for a complete picture of the situation by attending to a variety of instances.*

Two methodologies have been developed that help people accomplish these goals – scientific research and user-based design.

Scientific research is the more powerful debunker and the more time-consuming. It has developed over the centuries as a set of techniques by which errors in reasoning about empirical phenomena can be corrected. Discussion of the basic method is beyond the scope of this paper, but guidelines for the evaluation of bodies of research were provided and exemplified in two areas of research on the effectiveness of visuals presented with text. Because the findings are consistent and extensive, practical principles could be derived from these areas:

- Visuals sometimes are ineffective or even interfere with learning. Examples of such situations are when pictures are merely decorative or when the visual fails to capture the essence of the situation.
- Visuals facilitate learning and problem solving when they
  - a *help learners search through multifaceted information,*
  - b *when the visual makes explicit crucial features of the problem that is implicit in the text and*
  - c *when the visual organizes and integrates complex information.*

In addition, visuals facilitate memory when they represent
the text even if they do not fill the above criteria.

- Features not in the service of the informational content can be counterproductive.

When scientific principles are not available, designers can use the methodologies of user-based design to help guard against judgmental reasoning errors. In user-based design, the designers collect data (often by informal means rather than by the rigorous formal data collection techniques of science) from users at various stages as the design is developed. The designers develop a rough prototype, scenario or simulation that puts the user more or less in the position that they would be using the finished product and asks them to respond as if it were the finished product. This feedback provides the basis for subsequent revision of the prototype and the cycle is repeated until the designers have answered all their questions and those of the users. Although user-based design lacks the rigorous methodological control of scientific research and thereby is more prone to error, it can improve on typical human reasoning in that it seeks behavioral feedback from users (the more systematic and carefully this is done, the more likely the outcome will be valid) and provides an opportunity for designers to explore alternative hypotheses and alternative solutions.

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Tools for Worldmaking

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A view long venerated in philosophy and science separates image and word into separate worlds. Images resemble their referents or ideas of their referents. They present themselves all at once and lack clear linguistic procedures like syntax for ordering and decoding. Words, on the other hand, describe rather than resemble and are read linearly in time. Images are rich but diffuse in meanings, while words have less dense meaning and are more precise. The two do not translate directly into each other. These dichotomies reflect an ideological split between literal and metaphorical, true and fictional, scientific and artistic. Word and image often operate as unwitting stand-ins in this struggle. But the differences between word and image are smaller than they might seem. One area where the function of image is most like word is in graphs. The graph is a culturally given way of reading – a visual organization as language. It provides a means of systematically thinking about how we use such language without realizing it. Is there an understanding of how graphing as a technology functions? Investigation of this leads to considering ways of looking at and of understanding visual organization in order to put forward some alternative goals.

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[1] Language is often described as either a verbal form, related by ear as distinct from eye, or if written, as an encrypted form. These distinctions cleave language to avoid recognition of the fact that written language is performed visually.

[2] In this article, graph is the largest term, it contains map, chart and diagram.