Metaphor in Diagrams

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Abstract

Modern computer systems routinely present information to the user as a combination of text and diagrammatic images, described as “graphical user interfaces”. Practitioners and researchers in Human-Computer Interaction (HCI) generally believe that the value of these diagrammatic representations is derived from metaphorical reasoning; they communicate abstract information by depicting a physical situation from which the abstractions can be inferred.

This assumption has been prevalent in HCI research for over 20 years, but has seldom been tested experimentally. This thesis analyses the reasons why diagrams are believed to assist with abstract reasoning. It then presents the results of a series of experiments testing the contribution of metaphor to comprehension, problem solving, explanation and memory tasks carried out using a range of different diagrams.

The results indicate that explicit metaphors provide surprisingly little benefit for cognitive tasks using diagrams as an external representation. The benefits are certainly small compared to the effects of general expertise in performing computational tasks. Furthermore, the benefit of metaphor in diagram use is largely restricted to mnemonic assistance. This mnemonic effect appears to be greatest when the user of the diagram constructs his or her own metaphor, rather than being presented with a systematic metaphor of the type recommended for use in HCI.

Acknowledgements

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The students and fellows of Darwin College have broadened my horizons, developed my confidence, and demonstrated the inestimable value of small, multi-disiciplinary academic communities.

Thomas Green's work of over 20 years was the inspiration for this project; I am very fortunate that he accepted me as a student. That he has also been patient with my errors and encouraging of my ambitions was far more than I expected. I am tremendously grateful for the hours that Thomas has given me, especially after his departure from the Applied Psychology Unit and from Cambridge.

I would never have aspired to academic research, and could certainly never have contemplated this project, without the encouragement and enthusiasm of my wife, Helen Arnold. Fifteen years of marriage already deserves more than a declaration of love and gratitude – after the last three years of study, I look forward to Helen's acceptance of repayment in kind.

Table of Contents

Chapter 1: Introduction

> *These circles, or rather these spaces, for it is of no importance what figure they are of, are extremely commodious for facilitating our reflections on this subject, and for unfolding all the boasted mysteries of logic, which that art finds it so difficult to explain; whereas by means of these signs, the whole is rendered sensible to the eye.*
>
> *Letters of Euler to a German Princess, tr. H. Hunter 1795, p. 454.*

For 20 years, new computer software has presented information graphically as well as in textual form. The usual justification for this practice has been that the graphical form is easier to learn, understand and apply because it allows metaphorical reasoning. Consider these forthright statements from introductory textbooks on software user interface design, all published within the last two years: "Designers of systems should, where possible, use metaphors that the user will be familiar with." (Faulkner 1998, p. 89). "Metaphors are the tools we use to link highly technical, complex software with the user's everyday world." (Weinschenk, Jamar & Yeo 1997, p. 60). "Select a metaphor or analogy for the defined objects … real-world metaphors are most often the best choice." (Galitz 1997, p. 84). "Real world metaphors allow users to transfer knowledge about how things should look and work." (Mandel 1997, p. 69). "Metaphors make it easy to learn about unfamiliar objects." (Hill 1995, p. 22). "Metaphors help users think about the screen objects much as they would think about real world objects." (Hackos & Redish 1998, p. 355). "Very few will debate the value of a good metaphor for increasing the initial familiarity between user and computer application." (Dix et. al. 1998, p. 149).

The goal of this dissertation is to investigate the psychological evidence for these claims. This investigation is perhaps overdue. Not only are computer science students advised to use metaphor as the basis for their designs, but software companies routinely base their research efforts on this assumption (Blackwell 1996d), and the most influential personal computer companies insist on the importance of metaphor in making computers available to everyone:

> *You can take advantage of people's knowledge of the world around them by using metaphors to convey concepts and features of your application. Use metaphors involving concrete, familiar ideas and make the metaphors plain, so that users have a set of expectations to apply to computer environments.*
>
> "Metaphors" from Chapter 1 of the *Macintosh Human Interface Guidelines*. (Apple Computer, Inc. 1992).

> *Familiar metaphors provide a direct and intuitive interface to user tasks. By allowing users to transfer their knowledge and experience, metaphors make it easier to predict and learn the behaviors of software-based representations.*
>
> 'Directness', from *Windows Interface Guidelines for Software Design* (Microsoft Corp. 1995).

The conclusion of the research described in this dissertation will be that the case for the importance of metaphor is greatly over-stated. This should not be interpreted as a deprecation of graphical user interfaces. Graphical user interfaces provide many advantages – the problem is simply that those advantages are misattributed as arising from the application of metaphor. A more prosaic explanation of their success can be made in terms of the benefits of "direct manipulation", which indicates potential actions via the spatial constraints of a 2-dimensional image. The concept of direct manipulation has been thoroughly described and analysed (Shneiderman 1983, Lewis 1991). It will not be discussed in any detail here, but the implication of the current investigation is that, if the expected benefits of metaphor have been exaggerated, these low-level virtues and by-products of direct manipulation are even more important than is usually acknowledged.

Overview of the Thesis

Chapter 2 considers previous work in HCI, but it also reviews theories that have been proposed to describe diagrammatic graphical representations and to describe metaphor. It then considers the manner in which diagrams and metaphors can be used as cognitive tools, before returning to the question of HCI.

Chapter 3 presents the results of three contrasting surveys, investigating how computer scientists and professional programmers regard their use of visual programming languages. Researchers developing these languages are greatly influenced by cognitive theories, including some theories of metaphor, but professional users appear to have little awareness of the potential cognitive implications of diagrammatic representations, instead emphasising more pragmatic benefits.

Chapter 4 describes two experiments which manipulated the degree of metaphor in diagrams. The metaphor was used to teach elements of a visual programming language, then of more general diagrams, to people who had never programmed computers. Their performance was compared to that of experienced computer programmers, in order to judge the effect of the metaphor on learning. The use of metaphors provided little benefit relative to that of experience.

Chapter 5 investigates which properties of visual representations assist the formation of complex abstract concepts in visuo-spatial working memory. The value of mental imagery as a design strategy for abstract problems is an underlying assumption of much of the literature on visual metaphor. Four experiments were conducted to measure productivity when the appearance of the visual representation was manipulated. Metaphorical content appeared to have little influence, and there was also little consistent evidence for significant benefits from mental imagery use.

Chapter 6 returns to the type of explanatory diagram introduced in chapter 4, and presents the results of three further experiments which manipulated both the metaphorical and visual content of the notations. Diagrams were described with and without instructional metaphors, and both memory and problem solving performance were measured. Metaphor had little effect on problem solving, and memory was improved far more by pictorial content in the diagram than by explicit metaphorical instructions.

Chapter 7 concludes that the main potential advantage arising from metaphor in diagrams is a mnemonic one, rather than support for abstract problem solving or design with mental images. Furthermore the mnemonic advantage is greater if diagram users construct their own metaphors from representational pictures, rather than receiving metaphorical explanations of abstract symbols. This finding has considerable importance for the future study of diagram use and human-computer interaction.

Chapter 2: Diagram and Metaphor as Tools

> *As no image can be formed of abstract ideas, they are, of necessity, represented in our mind by particular, but variable ideas; and if an idea bear any relation to quantity of any kind, that is, if it admit of the modification of greater and less, though the archetype, as it is called, of that idea be nothing that is the object of our senses, it is nevertheless universally represented in our mind by the idea of some sensible thing.*
>
> *A Description of a Set of Charts of Biography, J. Priestley, 1804, p. 5.*

This chapter reviews previous research that has investigated the application of both diagram and metaphor as cognitive tools. Much research into the use of diagrams has not considered the possibility that metaphor might be involved. Likewise, much research into metaphor has explored metaphor in language rather than in diagrams. The chapter is divided accordingly. After brief definitions of diagrams and of metaphor as subjects of psychological research, the bulk of the review considers how each can be studied as tools.

The section that discusses diagrams as tools considers general theories of external representation use in problem solving, then addresses two specific cases that have been studied in greater detail: graphs and visual programming languages. The section that discusses metaphor as a tool concentrates on the previous research in human-computer interaction that has motivated this study, as described in the introduction to chapter 1. It is this research that suggests a possible relationship between theories of metaphor and of diagram use, despite the fact that there is relatively little empirical evidence to support some of the main theories.

Diagrams

Although this project originated in the study of graphical user interfaces, the methods and conclusions are applicable to a broader class of *cognitive artefact* (Norman 1991, Payne 1992) – diagrams. Diagrams are familiarly associated with instruction manuals (Gombrich 1990), electronics (Newsham 1995, Petre & Green 1990), software design (Martin & McClure 1985), architecture (Porter 1979), geometry (Lindsay 1989, Netz in press), general mathematics education (Pimm 1995, Kaput 1995) and symbolic logic (Shin 1991, Sowa 1993) as well as informal problem-solving (Katona 1940). Insights from these various fields are slowly being integrated in the interdisciplinary study of Thinking with Diagrams

(Glasgow, Narayanan & Chandrasekaran 1995, Blackwell Ed., 1997), with conclusions that are more widely applicable to other notations, including such examples as music notation (Bent 1980), board games (Ellington, Addinall & Percival 1982) or proposals for a pictographic Esperanto (Shalit & Boonzaier 1990).

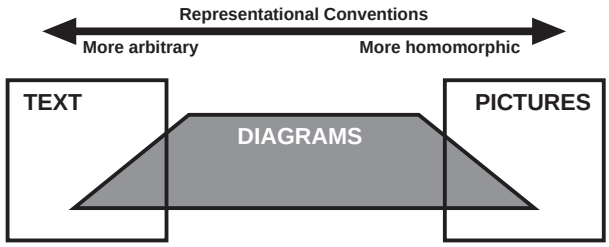


Figure 2.1. Continuum of representational conventions in cognitive artefacts

Within this huge range of applicability, the common nature of diagrams is most appropriately defined by contradistinction. Diagrams form the middle part of a continuum between two other classes of cognitive artefact: text and pictures (see Figure 2.1). If we regard all three as *markings* (Ittelson 1996) on some surface (setting aside the tasks to which they might be applied), diagrams can be distinguished from text by the fact that some aspects of a diagram are not arbitrary but are homomorphic to the information they convey. They can be distinguished from pictures by the fact that some aspects must be interpreted by convention, and cannot be deduced from structural correspondences.

A simple distinction underestimates the complexity of text and pictures, however. The cognitive processing of text is closely related to auditory verbal comprehension, and therefore inherits homomorphic features of speech: onomatopoeia, for example (Werner & Kaplan 1963), as well as typographic conventions and conjectured systematic origin of all abstract verbal concepts in spatial experience (Jackendoff 1983, Johnson 1987, Lakoff 1987). The construction and interpretation of pictures also relies on some arbitrary depictive conventions (Willats 1990), even though those conventions may simply reflect basic perceptual abilities (Kennedy 1975) and have been supplemented by the mechanical determinism of photography (Ivins 1953). For the purposes of the current argument, text and pictures can be regarded as ideals – extremes that are never observed in actual communication via markings. Instead, all texts are to some extent diagrammatic, and all pictures are to some extent diagrammatic. Even a photograph, despite the implied objectivity of mechanical reproduction, conveys information diagrammatically through its composition, its context on a surface and other factors (Stroebel, Todd & Zakia 1980).

As diagrams share aspects of both text and pictures, they can be analysed using techniques and theories from either extreme of the continuum. Firstly, diagrams can be regarded as two-dimensional graphical languages, composed from a lexicon of geometric elements. The relationship between these elements can be described in terms of a syntax incorporating various subsets of proximity, ordering, spatial enclosure and topological connection. Interpretation of a diagram is therefore a process of deriving semantic intention from the syntactic relationships that have been created between the lexical elements (Bertin 1981). This view of diagrams suggests that researchers should use the structural analysis of Saussure (Culler 1976), or the semiotic trichotomies of Peirce (1932).

Alternatively, diagrams might be regarded primarily as representations of physical situations. If they communicate any abstract information, this would involve metaphorical reasoning, for example relating the "upward" direction on the page to an increase of some abstract quantity (Gattis & Holyoak 1996, Tversky, Kugelmass & Winter 1991). The individual elements of a diagram may also be actual pictures, in which case they might be interpreted metaphorically as representing abstract concepts (Barnard & Marcel 1978).

Metaphor

Is it justified to apply the word *metaphor* to diagrams? Metaphor is usually understood in a verbal context; specifically as a figurative literary device or *trope*. Like irony, hyperbole and other tropes, metaphor is identifiable by the fact that the literal meaning of the words is not the meaning intended. There is instead a figurative meaning, which the hearer must establish by deduction from the context of the utterance, from knowledge of the world, and by constructing theories regarding the speaker's intention. The cognitive resources involved in this interpretive process are sophisticated – children have difficulty in understanding both irony and metaphor (Winner & Gardner 1993).

Aristotle's Poetics accords great respect to the value of metaphor ("... by far the greatest thing is the use of metaphor. That alone cannot be learnt: it is the token of genius" xxii. 17), and contains a detailed analysis of the way that metaphor works:

> *It is the application of a strange term either transferred from the genus and applied to the species or from the species and applied to the genus, or from one species to another by means of analogy.*
>
> Aristotle, Poetics xxi. 7

Modern cognitive theories of metaphor have often emphasised only a single aspect of this analysis. Glucksberg and Keysar (1993), for example, emphasise that metaphors are

expressed and understood as statements about class inclusion (i.e. genus and species), where the target of the metaphor inherits attributes from elsewhere in some categorical hierarchy. Gentner, Falkenhainer and Skorstad (1988), on the other hand, emphasise that understanding a metaphor is the same as drawing an analogy – it involves the mapping of structure and attributes from one domain to another.

A third cognitive theory of metaphor emphasises the metaphors that have "fossilised" into idiom. Lakoff and Johnson (1980) claim that individual idioms can be related to systematic collections of metaphorical concepts. For example, when Aristotle describes Empedocles' use of the metaphor "the evening of life" (Poetics, xxi. 13), Lakoff and Johnson might observe that there are many other idioms relating stages of life to time of day, and that these reflect an underlying conceptual metaphor such as "LIFE IS A DAY". Johnson (1987) and Jackendoff (1983) have both proposed theories in which all abstract language must be derived from embodied physical experience. Johnson describes this process as metaphorical, but Jackendoff objects (1983 p. 209) that the equation of physical analogy with metaphor is facile. The necessary grounding of abstraction in physical experience is a view that Black (1993) attributes first to Carlyle. It is supported by Lakoff and Johnson's conceptual metaphor proposal, and by Gentner and Wolff's (1997) "career of metaphor" hypothesis, but these are vigorously debated in cognitive psychology; Murphy (1997), for example, claims that Lakoff and Johnson's collection of metaphors involving the vertical direction simply neglects the polysemous multiple meanings of the word "up", while Gibbs (1996) defends conceptual metaphor from a review of experimental investigations of idiom comprehension.

There are numerous other theories of metaphor interpretation, some of which are supported by experimental evidence. Chomsky's anomaly model of metaphor processing, for example, suggests that we first evaluate the literal meaning of the metaphor, then reject that as a result of identifying an anomaly. Pynte et. al. (1996) studied the time-course of metaphor comprehension, and found evidence from event-related potential observations that the literal meaning of a metaphoric phrase was indeed evaluated before the figurative meaning. Tourangeau and Sternberg's interaction view of metaphor (1982) claims that aptness is increased by semantic separation between the source and target domains of the metaphor, because an apt metaphor must involve reorganising the hearer's understanding of the target domain. These and other theories of metaphor are less commonly investigated in cognitive psychology, and to my knowledge have never been applied either to diagrams or to HCI. They are not considered any further here.

This discussion provides several alternative models for addressing the role of metaphor in diagrams. If Gentner's structure mapping theory of analogy (1983) is also involved in

processing metaphor, it might be better to describe diagrams as *analogies* rather than metaphors. The value of diagrams in solving problems of structural analogy has certainly been demonstrated (Beveridge & Parkins 1987). If this is the only sense in which diagrams are metaphorical, they can be described in terms of structural geometric properties, rather than requiring any consideration of pictorial depiction. Alternatively, if diagrams are interpreted in terms of their resemblance to physical objects and situations, they should be analysed in terms of class inclusion. If this is the case, there is perhaps a more appropriate term applied in the visual arts. A painting in which the elements represent abstract concepts in the class they belong to is described as an *allegory* rather than a metaphor.

Is there any good reason why we should describe diagrams as metaphors rather than as structural analogies or pictorial allegories? There are three reasons why it is convenient to do so. Firstly, the field of HCI has adopted the term metaphor, while being unaware of many of the cognitive theories described above (although Gentner, Falkenhainer and Skorstad (1988), explicitly reject the suggestion that their model of metaphor applies to user interfaces, and Jackendoff (1983) insists that metaphor is more complex and subtle than physical analogy). Secondly, there is also a small existing literature outside the fields of psychology and HCI that has described the interpretation of diagrams as a process of metaphor: in education (Goldsmith 1984) in graphic design (Richards 1997) and in comic book art (Kennedy, Green & Vervaeke 1993). Thirdly, theories of conceptual metaphor have been explicitly extended from language to diagrams (Lakoff 1993). Some interpretations of conceptual metaphor claim that even linguistic metaphors are interpreted with the aid of mental images. Gibbs and O'Brien (1990) found that subjects were able to report causal relationships from images formed when interpreting a metaphor, although Cacciari & Glucksberg (1995) reported that identification of paraphrased metaphors was slower when such images were formed. The implied relationship between diagram use and these theories of metaphor interpretation is reviewed in more detail in chapter 5.

Diagrams as Tools

This thesis considers three broad categories of cognitive task in which diagrams are applied as tools. They are often used for communicating information, both as isolated presentations (e.g. statistical graphs) and as instructional material supporting a text (e.g. textbook illustrations). Secondly, they are used during problem solving, as external representations that supplement working memory and efficiently express problem constraints. Thirdly, they are used as an aid to discovery, generating potential configurations and exploring alternative

solutions. This thesis emphasises instruction, for which relevant literature is reviewed in chapter 4, and discovery, for which relevant literature is reviewed in chapter 5. Most existing research into diagram use emphasises problem solving – that research is summarised in this section.

Diagrams as Tools in Problem Solving

Although diagrams may depict relationships in the real world, and may stimulate mental imagery, it is not necessary to assume any resemblance to visual scenes (Goodman 1969), or causal relationship to mental images (Scaife & Rogers 1996). Most theoretical treatments of diagram use simply consider their geometric structure, rather than the metaphorical possibilities discussed in this thesis. Larkin and Simon (1987) attributed the benefits of diagram use during problem solving to three main information-processing operations. Diagrams can express correspondences between elements without requiring that labels be defined for those elements. Secondly, they can group together information that will be needed at the same time, thus reducing the amount of search required during problem solving. Thirdly, they support "perceptual inferences" by which information can be read directly from the diagram.

Bauer and Johnson-Laird (1993) have extended Larkin and Simon's analysis of geometric correspondences in diagrams. They demonstrated that subjects were faster and more accurate when answering a question based on a two-branch electrical circuit diagram than when answering a logically equivalent verbal question involving double disjunction. The geometric strategy used by subjects in this experiment is even more straightforward than that modeled by Larkin and Simon: subjects could use the diagram to answer the question simply by tracing (or imagining tracing) the lines of the circuit with a finger. Green (1982) has however noted the restrictions of this type of diagram – there are only a limited number of "mental fingers" that can be maintained when tracing flow through a complex diagram.

The perceptual inferences described by Larkin and Simon may simply involve low-level visual processing of boundaries (Ullman 1984) – either assessing three dimensional shape (Hoffman & Richards 1984, Grossberg 1997) or two dimensional figures (Palmer & Rock 1994, Shimaya 1997). They also enable impressive performance on computationally intensive tasks such the "travelling salesman" optimisation problem, for which MacGregor and Ormerod (1996) demonstrated that untrained experimental subjects could produce solutions that were more optimal than the best available computational algorithms. In the case of diagrams, Lindsay (1988) has demonstrated that perceptual processes make explicit information that was only implicit in an original construction. Lindsay also observes that this

kind of reasoning with spatial representations avoids the *frame problem* – knowing which aspects of a situation remain unchanged as the result of some action – because the scope of action is defined by spatial locality. This advantage also underlies the benefits of "direct manipulation", to which I attributed the success of graphical user interfaces in chapter 1.

Zhang (1997) has proposed a cognitive model of diagrammatic representations in problem solving that integrates the computational aspects observed by Larkin and Simon. He contrasts the perceptual operations afforded by external representations with the internal representations that support cognitive operations, including the retrieval of information from memory. Both internal and external representations provide different means of a) looking ahead to simulate future problem states, b) applying learned knowledge, or c) acting on the basis of pre-existing biases that apply in a particular modality (Gestalt principles of perception, for example, are a perceptual bias which reveal certain properties in an external representation). The interaction between internal and external representations has also been expressed in a computational model described by Tabachnek-Schijf, Leonardo and Simon (1997). This model constructs lines on a simulated blackboard, then inspects the blackboard to notice emergent properties, such as places where lines intersect. The graphical information is stored in a memory array representing visual working memory, but is also related to propositional knowledge about the meaning of the lines. The latter is stored in an approximate (non-phonological) model of verbal working memory.

Expert problem solving, such as that studied by Tabachnek-Schijf and Leonardo, is characterised by a repertoire of different diagrams and other representations, each of which may facilitate a different range of tasks (Sloman 1995). Cox and Brna (1995) have demonstrated the importance of teaching students how to select an appropriate diagram or other representation, in addition to teaching the skills required to construct a diagram and read information off from it. Whether the choice is successful or not depends on the extent to which the diagram constrains the possible interpretations (Wang, Lee & Zeevat 1995, Stenning & Oberlander 1995). The analysis of information transfer between multiple representations requires a sophisticated theory of information, as well as experimental evidence, however. The Hyperproof system (Barwise & Etchemendy 1990), successfully used to teach propositional logic, models logical relations both algebraically and in an imaginary three-dimensional world. A formal description of the relationship between the model, the real world, and the symbolic system depends on very fundamental issues in philosophy of semantics (Barwise & Perry 1983).

Diagrams as Tools: The case of graphs

Graphs constitute a class of diagram so conventionalised that a graph can stand alone without explanatory text. Gillan (1995) has demonstrated that after simple training in graph use, subjects can successfully interpret complex arithmetic relationships that otherwise require complex problem solving. Graphs are so widely used by experimental psychologists themselves that they have perhaps attracted an undue degree of research attention. Detailed studies have been made of the semiotic (Kosslyn 1989) and perceptual properties of graphs (Hollands & Spence 1992, Spence 1990, Pisan 1995), as well as of interpretative behaviour (Zacks & Tversky 1997, Stone & Yates 1997, Carpenter & Shah 1998) and cross-cultural analyses (Tversky, Kugelmass & Winter 1991). Some of these studies have provided practical advice about when to use graphs in presenting research results (Carswell & Ramzy 1997, Shah & Carpenter 1995).

Applied research tends to focus on the question of what notation will be most suitable in cases where a choice can be made. In the case of graphs, this has been a focus of attention for many years. Washburne (1927) made a classic comparison of numerical data presented as graphs and tables, showing that graphs allow more rapid judgements. Meyer (1997) has recently reinvestigated Washburne's data, however, showing that his conclusions were unjustified – they have simply not been questioned because they were unsurprising. Similar problems pervade this type of research. Tufte's (1983, 1990) books on the design of quantitative graphs and other diagrams have been hugely influential in software design. They are not unequivocally supported by empirical evidence, however (Spence 1990, Zacks et. al. 1998). Tufte expresses various assumptions about readability and usability, but they amount largely to the personal (modernist) tastes of a practitioner. In recent years, these tastes are being supplanted by post-modern styles including pictures, tables and diagrams within the same frame (Wurman 1997). Although fashionable at the time of writing, post-modern information graphics have no more foundation in empirical research than Tufte's work. This is unlikely to prevent their increasing adaptation from American news media to applications in software design.

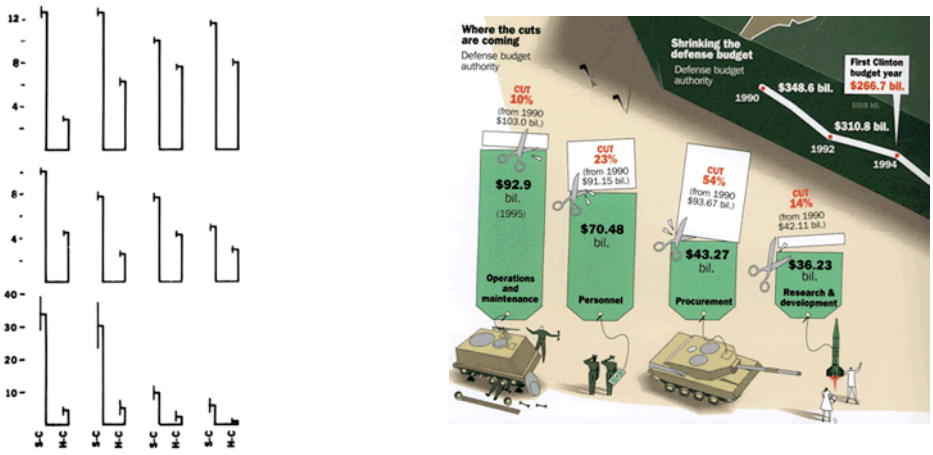


Figure 2.2. Examples of graphical presentation styles recommended by (a) Tufte and (b) Wurman. [Sources: (a) from Tufte 1983, (b) from Wurman 1997]

Diagrams as Tools: The case of visual programming languages

This study originated in a commercial software product development project, designing a new visual programming language (Blackwell 1996d). Visual Programming Languages (VPLs) often resemble the diagrams used by computer programmers during the design process, but they are used directly by the computer – a VPL specifies program behaviour to a level of detail sufficient that the program can be executed with no further manual intervention. The development of VPLs can be traced to research by Sutherland (1963) and Smith (1977); the range of VPLs created since then has been surveyed by Myers (1986) and by Price, Baecker & Small (1993). Researchers generally draw a distinction between VPL research, and the range of programming environments marketed by Microsoft Corporation, including Visual Basic, Visual C++ and Visual Java. Although those products were presumably named to reflect the endeavours of VPL research, they differ from VPLs in that the program behaviour is specified using a conventional textual programming language rather than any kind of diagram.

Visual programming languages are an interesting topic of study in cognitive psychology, both because programming is a complex problem-solving activity, and because VPLs include a wide range of alternative diagrammatic representations (Blackwell, Whitley, Good & Petre, in press). Psychological research into the use of diagrams for programming predates the development of VPLs, in fact (Fitter & Green 1979). As commercial VPLs have become more widely available Green has, with various collaborators, published a substantial body of

research investigating their cognitive implications (e.g. Green 1982, Gilmore & Green 1984a, Green, Petre & Bellamy 1991, Green & Petre 1992, Green & Blackwell 1996a).

Green's work has emphasised the nature of programming languages as information structures (Green 1990) – the question of whether the structure of the notation does or does not match the structure of the task is more important than the question of whether text or diagrams are used (Gilmore & Green 1984b). Green's analysis of information structures and the way they are used has been unified and extended in the Cognitive Dimensions of Notations framework (Green 1989, Green & Petre 1996). This approach to comparing the relative advantages of different programming languages is contrasted with the *superlativist* claims often associated with VPL research – that VPLs will be superior for all possible programming tasks (Green, Petre & Bellamy 1991). The contrast between empirical results and the superlativist position will be investigated in detail in chapter 3.

Diagrams as Tools: Empirical investigations

If graphs lie at one extreme of the diagrams that are studied experimentally, the other might be programming languages. Graphs are widely used, can often be interpreted independent of context or task, and might be considered a requirement of basic literacy. Programming languages, on the other hand, support complex problem solving and interaction between specialist users. Other diagram applications considered in human factors research, such as vehicle instrumentation or design of instructional material, generally fall between these extremes. Major themes in the empirical investigation of thinking with diagrams are often represented by experiments at each point along this continuum of complexity and context. As an example, Lohse (1997) has used gaze fixation analysis to identify the ways that layout conventions modify working memory requirements in graph interpretation. Chandler and Sweller (1996) have estimated working memory requirements (in the context of "cognitive load") that arise from the attempt to integrate text and diagrams in instructional material. Davies (1996) has investigated working memory requirements in programming by modifying the environment in which a program is written, thereby changing the extent to which experts can use the notation as an external representation to assist problem solving. A further example is the various investigations that have been made of structure in diagrams, and how it influences interpretation. Bennett and Flach (1992) have reviewed various perspectives on interpretative processes of information displays, such as Wickens and Carswell's (1995) proximity compatibility principle relating display location to function. Green's Cognitive Dimensions of Notations (Green 1989, Green & Petre 1996) describe the way that notational design can affect the tasks involved in constructing and modifying as well as interpreting programming languages and other notations.

Metaphor as a Tool

Metaphor is often thought of as a literary device; in the context of literature it is certainly a tool used deliberately to achieve specific effects. It is also intentionally applied as a tool to other communicative contexts – most notably to education. All education is a process of communicating new information to students in such a way that they can assimilate it and relate it to what they already know (Gallagher 1978). Metaphor is used by teachers to communicate novel concepts, but always brings the danger that students may over-extend the metaphor and draw inappropriate analogies (Nolder 1991). Ideally metaphors are used to develop new concepts by a process of triangulation (Petrie & Oshlag 1993) – students recognise anomalies between their existing knowledge and new information provided by the metaphor, and create new knowledge by correcting their model to accommodate both sources. Spiro et. al. (1989) propose that sophisticated students can be assisted in this process if they are given multiple metaphors, each correcting invalid extensions that might have been based on a single one.

Where the intention is to communicate purely abstract concepts however, it may be unreasonable to expect that pure abstractions can be derived from physical examples. Pimm (1995) observes that it is unhelpful to consider mathematical concepts as being independent of their representations, and describes the goal of mathematics education as learning to manipulate representations. If the goal is specific to the representation, then the use of physical metaphors (common in mathematics education) may even be detrimental to the goal of learning to do symbolic mathematics. In less abstract domains – physics for example – physical metaphors may of course help to form a simplified mental model of the situation being described. Mayer (1993) describes an experiment in which recall of physical principles was improved when radar operation was described metaphorically.

Metaphor as a Tool in Human-Computer Interaction

The application of metaphor to user interfaces can also be justified on educational grounds. The main obstacle associated with user interfaces is often described as a “learning curve” – the quotes from user interface textbooks in chapter 1 make it clear that metaphor is expected to remove this obstacle by allowing users to build on their experience from other areas. A secondary advantage of metaphor in HCI may lie in support for problem solving. When users experience problems with the device, they can solve those problems by analogy to solutions that might be applied in the metaphor domain. There is a substantial literature describing this analogical approach to problem-solving, based on various theories of analogy (Gick &

Holyoak 1983, Gentner 1983, Holland et. al. 1986, Mitchell 1993, Keane 1997). The visual representations of a graphical user interface, besides introducing pictorial metaphor, can also help users to form appropriate analogies by matching the problem to the surface features of an appropriate source domain (Keane 1988, Heydenbluth & Hesse 1996). Beveridge and Parkins (1987) carried out an experiment in which subjects were more successful at forming analogies after seeing diagrammatic representations that depicted the required configuration. Schunn and Dunbar (1996) have claimed, in fact, that the value of analogy lies simply in priming of an appropriate solution – that no transfer of abstractions is involved.

In the HCI literature itself, justifications of metaphor in the user interface are usually made in terms of one of these two research perspectives; either the metaphor assists the user to learn the underlying abstractions of the computer system, or it provides a basis for problem-solving while performing a specific task. An early analysis by Carroll and Thomas (1982) said that the importance of metaphor implied a fundamental critique of the level at which psychology is applied to user interface design. Metaphor was an essential attribute of a good user interface, and this could only be appreciated in terms of psychological theories. Early textbooks and collections of readings on human computer interaction always included some representation of this view (Carroll & Mack 1985, Carroll, Mack & Kellogg 1988) and detailed cognitive models have been proposed as a framework for evaluating metaphorical interfaces (Rieman et. al. 1994).

Several attempts have been made to systematise the process of user interface design from metaphorical foundations. Carroll has provided several sets of guidelines for designers, in the texts listed above. Wozny (1989) advises the designer above all to make the metaphor explicit, so that it is accessible to the user. Madsen (1994) has written a practical "cookbook" instructing user interface designers on how to choose and apply a metaphor to their design. A European research project has defined the formal characteristics of usable metaphors (Smyth, Anderson & Alty 1995). A layered structure has also been proposed for the design of database user interfaces, in which the data model is situated at the bottom level of the hierarchy and the metaphor at the top level (Catarci, Costabile & Matera 1995).

There have also been critics of the metaphorical user interface. Halasz and Moran (1982) claimed that users need to develop an abstract conceptual model, and that metaphor was only of passing value in building that model (in the sense of Lakoff and Johnson (1980) – that all abstractions have some linguistic metaphorical basis). Halasz and Moran claimed that drawing new analogies from a user interface metaphor in order to solve problems was dangerous, because so many invalid conclusions might be derived. Simos and Blackwell (1998) have revised this argument in terms of Green's Cognitive Dimensions of Notations (Green 1989, Green & Petre 1996). As noted above, Gentner, Falkenhainer and Skorstad (1988)

specifically discount the application of their structure mapping theory of metaphor and analogy to the analysis of user interfaces. Mohnkern (1997a) considers that a metaphor is useful only as a bundle of user interface affordances (Norman 1988) and that deeper systematic metaphors are likely to be misleading. It is certainly possible to find misguided applications of (mixed) metaphor, such as the (possibly disingenuous) observation by Akoumianakis and Stephanis (1997) that a pull-down menu is based on an underlying "restaurant" metaphor, or that the desktop metaphor is based on "sheets of paper called windows".

Empirical Investigations of Metaphor in HCI

The generally assumed theoretical benefits of user interface metaphor are supported by surprisingly little empirical evidence. Instead, one finds studies that appear to have set out with the goal of demonstrating the value of metaphor, but are eventually published with much weaker claims. Simpson and Pellegrino (1993), for example, carried out an experiment comparing a geographical metaphor of a file system to an unadorned flow chart. Despite participants' subjective preferences for the metaphor, no difference was observed in the performance of experts using either notation. Novices performed slightly better using the metaphor: the authors conclude only that direct comparison of the two forms is not justified because the tasks are not equivalent. It seems that a study which set out with the intention of demonstrating the benefit of metaphor failed to do so, and was published on other grounds.

Similar results are reported, with some surprise, by the human factors editor of *IEEE Software*. Potosnak (1988) reviews studies in which iconic interfaces performed poorly by comparison to command interfaces. She notes that these unexpected results are probably due to the fact that the iconic interfaces were poorly designed, and that the results do not necessarily cast doubt on the value of metaphor. Other studies have attributed unsatisfactory performance of metaphor to specific sub-groups within an experimental population; Rohr (1987) for example, reports complex interactions between personality characteristics and experimental task performance with graphical user interface metaphors. Those studies which have reported unambiguous benefits from metaphor use do not assume too much about the educational benefit of the metaphor. Schweiker and Muthig (1987), for example, describe the spatial metaphor as supporting "naive realism" – a concept apparently identical to direct manipulation. As mentioned at the start of this chapter, there is little doubt that direct manipulation is responsible for the success of graphical user interfaces; it is the more substantial claims about metaphor that give cause for doubt.

Origins of Metaphor in HCI

The idea that a user interface should be metaphorical is so widespread that it is dangerous to attribute it to a single source. Most general concepts in computing (the "bug", for example), far predate the invention of computers; anecdotal reports of their invention (Grace Hopper discovers short circuit caused by moth) are usually either apocryphal or epiphenomenal. Nevertheless, David Canfield Smith makes a strong claim (Smith 1996) to the invention of the "desktop" metaphor that has inspired all of the research described here. His PYGMALION system (Smith 1977) was developed in the Stanford AI Lab, providing the basis of the Xerox Star (Smith et. al. 1982, Johnson et. al. 1989), and subsequently the Apple Macintosh. PYGMALION's status as an AI project meant that it originally expressed a theory of cognition, and was never simply a software tool. It was not based on empirical studies of metaphor and analogy, however. Smith considered that PYGMALION would finally allow computers to be used for creative tasks, because its graphical nature corresponded directly to the mental imagery that forms the basis of creative thought. He based his argument in psychological theories of aesthetics (Arnheim 1970, Koestler 1964) rather than problem-solving. The "metaphor" in PYGMALION's graphical interface was there because "visual imagery is a productive metaphor for thought" (Smith 1977, p. 6). Smith's theory of creativity is seldom cited directly in the HCI literature, but it appears to have been influential in other areas of computer science, as will be seen in chapter 3.

Alternatives to Metaphor in HCI

This review has focused on the arguments that might be made for the value of diagrammatic metaphor in contexts such as HCI. It has not considered some fundamentally different approaches to the analysis of communication and representation. Blackwell and Engelhardt (1998) have made a more detailed study of the many different typologies that have been proposed for classifying and studying diagrammatic representations. Some of these are impressively detailed semiotic analyses of the potential space of graphical configurations (e.g. Twyman 1979). Alternative reviews have included cognitive historical analyses of the origins of graphical representations (Gregory 1970, chapters 8 and 9), naive classification of visual representations by experimental subjects (Lohse et. al. 1994) and classifications of the interaction between media types and sensory modalities (Stenning, Inder & Neilson 1995).

Many studies of HCI place it within a broader communicative context, in which the effectiveness of supposed metaphors can be criticised on social grounds (Bødker 1991, Nardi 1993, Nardi & Zarmer 1993), or in terms of the user's conversational interaction with the interface (Payne 1990, Strothotte & Strothotte 1997, Bottoni et. al. 1996). To use the word

metaphor in a different sense, each of these analyses describes HCI in terms of some contextual metaphor: a conversation metaphor, a social interaction metaphor, or others. Reddy (1993) has analysed the implications of the "conduit" metaphor for communication between people, and shown how it influences communicative intent. There have been similar critiques of HCI. Laurel (1986) deplores the fact that most user interfaces insist that the user is manipulating a tool, when people do not want to manipulate tools: they want to play games or search databases. Hutchins (1989) has made a collection of the different metaphors that might be applied to HCI – not only using a tool, or holding a conversation, but making a declaration, acting in a model world or collaborating with an intermediary. The topic of this thesis addresses a metaphor that is far more central in HCI – the user-interface-metaphor metaphor. It relies on two assumptions: that graphical representations are metaphorical, and that metaphors are valuable as cognitive tools.

Summary

This thesis evaluates the benefits of diagrammatic metaphor as a cognitive tool. Diagrams share some structural properties of language, and many of these can be analysed to explain how their structural characteristics assist with certain types of reasoning task. They can also be interpreted pictorially, in which case interpretation is a metaphorical process. Metaphor is an important educational tool, but the claims made for the value of metaphor in graphical user interfaces are more contentious. This thesis aims to supplement the studies of structural characteristics of diagram use, some of which also provide sufficient explanation for the benefits of graphical user interface. The research described here explicitly manipulates the metaphorical content of diagrams, while leaving the structure unchanged.

These results are applicable to many classes of diagram, even though they address the specific claims made by the HCI community. The point at which those claims become most relevant to other diagrams is in the discussion of visual programming languages – complete and sophisticated diagrammatic tools with a clearly defined semantics that can be applied to a broad range of problem solving tasks. The instructional benefits of metaphor should be clearly apparent in this class of diagram.

Chapter 3: Metacognition among Diagram Users

> *These paradigms change the very way you think. They lead to new habits and models of behaviour that are more powerful and productive. They can lead to a human-machine synergism.*
>
> *Smith, Irby, Kimbal, Verplank & Harslem (1982), p. 272.*

As described in chapter 2, a class of diagrammatic tools which support particularly complex problem solving is the class of visual programming languages (VPLs). VPLs are also unusual in that they have a relatively recent history compared to other types of diagram, and it is therefore possible to investigate the reasons why they have been developed and promoted. Green, with various collaborators, has made many empirical studies of VPL use. This empirical approach to comparing the relative advantages of different programming languages can be contrasted with *superlativist* claims for the superiority of VPLs (Green, Petre & Bellamy 1991). Several studies have supported Green's contention that superlativism is unjustified – the empirical evidence is reviewed by Whitley (1997), and dates back to comparisons finding no difference in performance between flowchart users and those writing plans in English (Soloway, Bonar & Ehrlich 1983).

Despite the paucity of empirical evidence, and the availability of analytic tools such as Green's Cognitive Dimensions, superlativism has been widespread in VPL research. At one level, superlativist claims might appear ridiculous, as though someone were advocating the replacement of written language with images (Dondis 1973, Barker & Manji 1989). In fact, some researchers candidly acknowledge the lack of empirical evidence for the benefits of their work, and suggest that novelty is sufficient justification for new notations to be developed (e.g. Hyrskykari 1993). Other developers of VPLs report negative findings after empirical evaluations of their own projects, but this is seldom regarded as a reason to abandon the project (e.g. Ladret & Rueher 1991, Grant in press). It is far more common, however, to expend considerable effort on designing graphical alternatives to existing textual notations without ever questioning why the textual notations are inadequate (e.g. Missikoff & Pizzicanella 1996).

This chapter does not evaluate the empirical evidence for and against visual languages, nor the theoretical considerations that cause an information structure to be well suited to a particular task. Instead, it investigates the *metacognitive* assumptions that underlie the superlativist claims made in VPL research. Those assumptions are generally based on the

beliefs that VPL researchers hold about the nature of problem-solving and programming, and about the nature and uses of diagrams. These metacognitive beliefs – beliefs about the nature of our own thought processes (Flavell 1979) – are important for several reasons. Firstly, metacognitive beliefs can have significant effects on the way that people choose cognitive tools. For example, many people believe that hiding an object in an unusual place will make it easier to remember. This particular metacognitive belief is unfounded (Winograd & Soloway 1986), a fact which is useful to know when planning one's household affairs.

Secondly, the metacognitive beliefs of VPL designers influence the choices that they make when designing new languages, and hence affect the characteristics of the languages themselves. These beliefs may not be questioned where they are in accordance with popular introspection, as observed by Meyer (1997) in his reanalysis of Washburne's classic study of graphs. Thirdly, metacognitive beliefs influence the strategies that people use when solving problems using diagrams (Schoenfeld 1983). Users of a VPL will similarly use the tool in ways determined by their own beliefs about the value of diagrams. Unfortunately, metacognition is not always an accurate guide for performance in comprehension and problem-solving: Glenberg, Wilkinson and Epstein (1982) found that 92% of experimental subjects were certain they had understood a passage that was actually self-contradictory, while Metcalfe and Wiebe (1987) found that success in solving insight problems was unrelated to subjects' expectations of their performance.

This chapter presents three studies of metacognitive beliefs. All three survey the opinions of experts regarding the cognitive advantages of VPLs, but the three survey populations have very different experiences of visual programming. The first survey investigates the metacognitive beliefs of VPL researchers, as published in the visual programming research literature. The second compares the opinions of experienced programmers who had not used a visual programming language. The third investigates the opinions of programmers who are experienced users of a commercially available VPL.

Survey 1: Metacognitive statements in the computer science literature

This first study investigates the systematic nature of metacognitive beliefs among VPL researchers. Other fields of computer science exaggerate the intuitiveness of the innovations they introduce, but the underlying assumption is often a straightforward simplification (such as the contention that an "object" in object-oriented programming is as easy to identify and manipulate as an object in the real world – Blackwell 1993). A corresponding simplification in VPL research (as in research into diagrams and illustration) might be an appeal to the

1920s marketing slogan, now would-be Chinese proverb "a picture is worth a thousand words" (Mieder 1990, Blackwell 1997a). The justification for VPL research is seldom so simple, however. This study investigates the range of statements that have been made by VPL researchers.

The results of this study have previously been published in Blackwell (1996b).

Population

The main source of data for this survey was a two-volume collection of well-known papers in visual language research, published by the IEEE (Glinert, Ed. 1990a, 1990b). This was supplemented by several textbooks on visual programming languages (Shu 1988b, Chang, Ed. 1990a, 1990b, Burnett, Goldberg & Lewis, Eds. 1995), by two volumes of the *Journal of Visual Languages and Computing*, and by a search for visual programming articles in two popular computer science journals (*Communications of the ACM* and *IEEE Software*) over the period after the publication of the Glinert collection. Approximately 140 publications were considered in all. The original publication dates ranged from 1977 to 1995, with a median year of 1988.

Method

The first stage in data collection involved the identification of passages in these papers where the research was justified, or the significance of the results discussed, in terms not directly derived from the technology described. These passages generally appeared in either the introduction or the concluding sections of the paper. A statement such as "visual programming languages will result in improved productivity because the human mind is optimised for vision" (not an actual quote from the study) would be a typical target for analysis.

Once these passages had been collected, they were divided into individual phrases, and each phrase was classified according to the theme that it addressed. This segmentation and classification was repeated at two different stages of the research. The initial classification (described in Blackwell 1996b) considered only the material collected in the current survey (i.e. it did not include distinctions discovered during the analysis of surveys 2 and 3), and was not based on any external reference point. The second classification considered material collected in all three of the surveys that are described in this chapter, and provided a common coding framework for all three sets of data. It is the later of the two classifications that is

described here. An analysis based on this second classification has been published previously by Whitley and Blackwell (1997).

The classification framework was based on an initial sample (20%) of the material from all three surveys, which was considered by two coders – coding decisions regarding this sample were discussed at length, in order to clarify the interpretation of each theme. A separate sample was used to assess inter-rater reliability at the end of the third survey. The theoretical motivation for the framework was mixed, addressing relatively independent research questions arising from the respective projects of Whitley and myself. Nevertheless, each phrase in the survey material was allocated uniquely to one theme in the classification framework. The allocation of phrases to independent research questions is most relevant in survey 3, and is discussed further there.

Sample responses

40 passages describing metacognitive beliefs were identified in the corpus of 140 research publications surveyed. In the following summary of the themes that were addressed, publications are identified by an index number. The actual publications are listed in table 3.1, with page numbers identifying the locations of those passages which were found within longer texts – full citations can be found in the bibliography.

1	Baroth & Hartsough (1995), p.22	21	Gutfreund (1987)
2	Brown & Sedgewick (1984), p.178	22	Huang (1990), p.68
3	Burnett & Ambler (1994)	23	Ichikawa & Hirakawa (1987)
4	Burnett, Baker, et. al. (1995)	24	Karsai (1995)
5	Chang, Ungar & Smith (1995), p.186	25	Kimura, Apte, et. al. (1995)
6	Chang (1987)	26	Kopache & Glinert (1988)
7	Chang, Costagliola et. al. (1995)	27	Lodding (1983)
8	Chang. (1990), p.2	28	Lord (1994)
9	Costagliola et. al. (1995)	29	Myers (1986), pp.59-66
10	Cox (1986), p.158	30	Pong & Ng (1983)
11	Cox & Pietrzykowski (1988)	31	Repenning & Sumner (1995)
12	Diaz-Herrera & Flude (1980)	32	Schiffer & Fröhlich (1995), p.201
13	Dillon, Kutty et. al. (1994)	33	Shu (1986)
14	Duisberg (1988)	34	Shu (1988a), p.662
15	Edel (1986)	35	Shu (1988b), pp.1,6
16	Ford & Tallis (1993)	36	Smith (1977)
17	Glinert & Gonczarowski (1987)	37	Tanimoto & Glinert (1986), p.54
18	Glinert & Tanimoto (1984)	38	Tripp (1988)
19	Glinert (1990), pp. 145, 148,170	39	Wood & Wood (1987)
20	Goldberg, Burnett & Lewis (1995), p.11	40	Yeung (1988)

Table 3.1. Survey sources in visual programming literature

Themes

The following discussion describes the themes that were used in the final classification of phrases from all three surveys. An overall hierarchical arrangement of the themes is illustrated in figure 3.1. Where superscript index numbers in brackets appear in the theme descriptions (e.g. "[31]") these refer to specific sources cited in table 3.1.

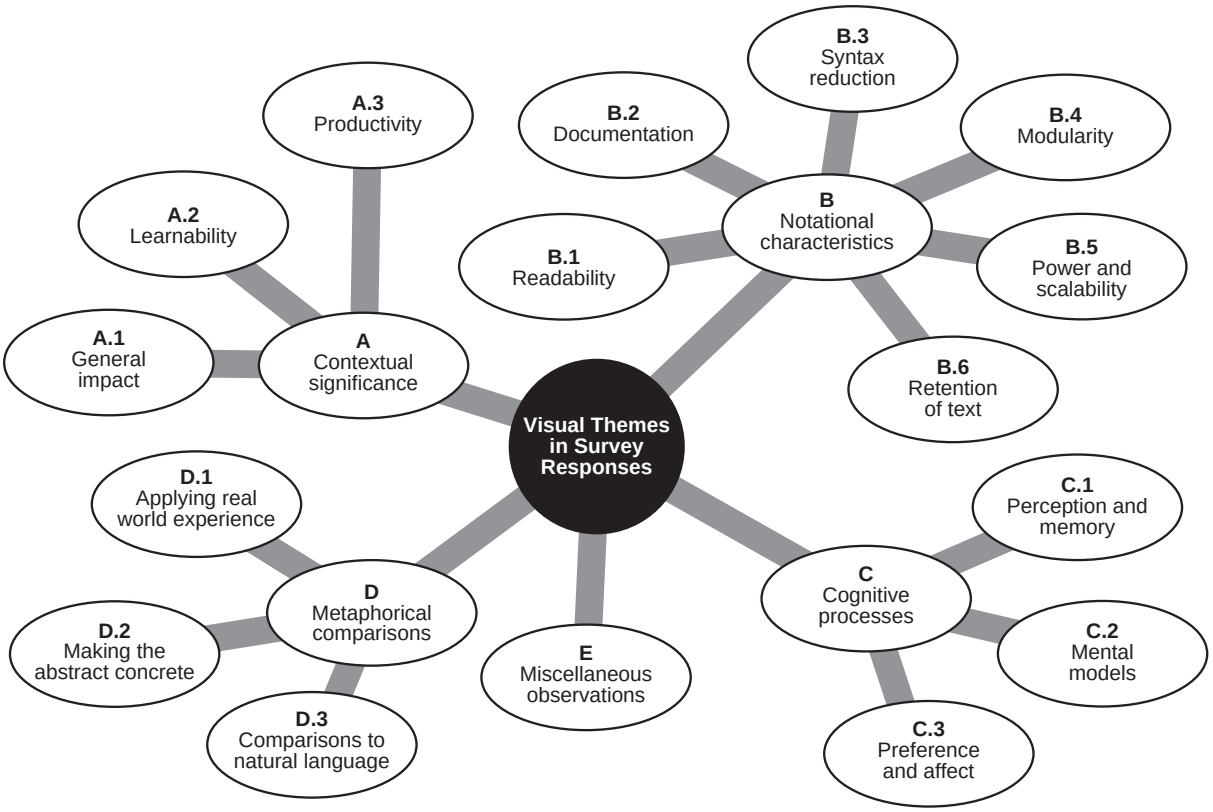


Figure 3.1. Hierarchical organisation of classification themes

A) Contextual significance

This category includes several themes describing the benefits that might be found when VPLs were applied to an actual task, possibly in a commercial programming environment. It is broken down into three themes: the first describes the general impact of VPLs, the second specifically considers the benefits of VPLs in learning to use a new language, and the third considers the productivity that can be achieved using a VPL.

A.1) General impact

Many statements found in this survey described visual languages as being easy to use (user friendly[8], helpful[19], straightforward[9], reliable[4] etc.) without mentioning any specific benefits or justifications. Often these statements were extended to claims about the particular relevance of VP to classes of users who may find textual programming to be too difficult (e.g. students[23,39] "end-users"[24], "common users"[7], or pre-literate children[37]). As no reasons are given for these statements, they can be regarded as direct expressions of the superlativism described by Green, Petre and Bellamy (1991). These statements provide little further ground for analysis, although it is interesting to note that it is apparently easy to

publish unsupported statements such as this in well-regarded scientific forums. Furthermore, the positive attributes described are not recognisably specific to programming.

A.2) Learnability

A very common statement of the main advantage of VPLs is that they will no longer require effortful learning or training[25,39], because they use skills that come naturally[12] use native intelligence[18] or are intuitively meaningful[7,9] even to people who are not familiar with computers[23]or computer illiterates[39]. Software developers often claim the virtue of intuitiveness for their interface designs, while being unclear of how this has been achieved. In the statements here, the main justification seems to be that the VPL can be understood immediately by analogy from previous experience. This belief is considered as the main concern of theme D.1, but it should be noted at this point that new notations are far more likely to require lengthy acquisition of expertise (Petre & Green 1993), rather than being accessible, immediate and obvious[37].

A.3) Productivity

Professional programmers are highly concerned with their productivity – how fast they can complete a project. For the professional, this is even more important than the ease of learning a new language, because learning a language is a worthwhile investment if it results in increased productivity. This issue is regularly mentioned in the two surveys of professional programmers, but also receives some attention in the research literature[19,32]. These are generally simple statements of opinion or anecdotal reports of widespread success[17], rather than citing any empirical evidence, although one of the papers covered in the survey does report an empirical comparison of projects using a VPL and a text language[1]. The reasons why a language might increase productivity include ease of use[4], of writing[29], and of modification[20]. Readability (theme B.1) possibly has even more impact on productivity, but it was the professional programmers in the second two surveys who were more likely to consider software development tasks other than coding.

B) Notational characteristics

This category includes those statements that concentrate on the characteristics of the notation itself, rather than the context in which it is used, or the cognitive processes involved in interpretation and creation. These other issues are always implicit, of course, so this is a matter of emphasis rather than discontinuity. The category is divided into six themes, most of which can be related to one or more of Green's cognitive dimensions (Green 1989, Green & Petre 1996): readability (hidden dependencies, visibility, diffuseness) is the most common concern when evaluating a notation; documentation (secondary notation, role expressiveness) describes the value of a notation for communicating with other people; and syntax reduction

(repetition viscosity, premature commitment) describes the ways in which a notation can obstruct manipulation. Modularity (abstraction gradient, knock-on viscosity) and power (diffuseness, abstraction gradient) consider whether the notation supports standard software engineering practice, while real projects also require programs that mix notations, because most software must process text, whether or not the program is created diagrammatically.

B.1) Readability

Respondents in the surveys of professional programmers (surveys 2 and 3) paid great attention to the value of a VPL in reading programs, rather than in creating them. They also tended to consider specific syntactic constructs or overall views of program function. Those responses are discussed in more detail later – the research literature sampled in this survey emphasised more general questions. Graphical notations were described as being generally easier to comprehend than text[41,37], largely because they explicitly represent meaningful relationships between elements[4,32]. This is in accordance with Larkin and Simon's (1987) model of locality and connectivity in diagram use. There is an element of overstatement, however – complex systems are unlikely to be trivially easy to comprehend[24], even when presented visually, because it is seldom possible to represent all possible relationships in two dimensions (the cognitive dimension of hidden dependencies). It is also suggested that a visual notation can better express the structure of the computer itself, so that we can understand its internal state[15] – this is a proposal which is investigated in experiment 1 in the next chapter. Readability is also compromised by the cognitive dimension of diffuseness – but researchers tended to claim that visual notations are less diffuse than text i.e. "a picture is worth ten thousand words", but with a scientific gloss "Pictures are more powerful than words as a means of communication. They can convey more meaning in a more concise unit of expression."[33]

B.2) Documentation

Programmers generally object to the drudgery of documenting the behaviour of code they have written. If a visual notation successfully communicates the intention of the designer[32,25], then additional documentation may be unnecessary. This question was of far more concern to professional programmers than to researchers, who were more likely to describe the same notational attributes in terms of the way that they directly express semantics during programme construction (B.3) or facilitate communication between members of a programming team or between designers and users of a system[1].

B.3) Syntax reduction

In the ideal intuitive programming language, no work would be needed to write a program. The user can express what they want naturally, and the programming work would be

"automatic"[24,33]. New programming languages have been described as automatic ever since the development of FORTRAN. The way in which VPLs achieve this goal is often expressed in a comparison between syntax and semantics; the programmer need not be concerned with the syntax of a program[32], which is of interest only to the computer. It is the semantics of the program, what it is supposed to do, that is important. These views perhaps reflect some confusion about the nature of linguistic syntax – some discussions suggest that *design* notations contain purely semantic information, which is 'translated' into syntax when the program is written (this is addressed further under theme C.2). This is taken to mean either that the translation process is unnecessary when a VPL is used[3] or that semantics and syntax can be divorced and even written down side-by-side in a visual environment[25]. The real concern underlying these statements is likely to come from programming languages that require syntactic elements purely for the convenience of the compiler: making sure that keywords are used, variable types defined or lines terminated by a semicolon[12]. It is as these "low-level" syntactic constructs are obviated by more intelligent compilers[24,31] that the main advances are achieved in each generation of 'automatic' programming.

B.4) Modularity

Support for modularity is an important attribute of any programming language. Surveys 2 and 3 were conducted during a period when modularity was being given paramount emphasis via the promotion of "object-oriented" programming languages. Discussions of the advantages of VPLs sometimes attribute those advantages to the ways that VPLs encourage modularity or object-orientation: by presenting modules as icons on the screen or by physically enclosing modules within a diagrammatic boundary, for example. Research publications tended to make a clear distinction between the advantages of visual programming and the advantages of modularity, however.

B.5) Power and scalability

Respondents in survey 2 often commented that VPLs were unlikely to be as powerful as the languages they already used. The definition of "power" in this case is open to debate. Some programmers consider the most powerful languages to be those which encourage the highest level of abstraction. Research publications do claim that VPLs are good at showing abstraction[2], or communicate a higher level of abstraction[32], while others note that abstract data is challenging for VP precisely because it is not inherently visual[8]. As will be discussed in survey 2, these respondents were more likely to be concerned about reduced access to lower levels of abstraction within the computer.

B.6) Retention of text

Respondents in surveys 2 and 3 often noted situations in which text would continue to be necessary, even when using a VPL. Research publications on visual programming were unlikely to make this criticism of VPLs, however. It is an observation that tends to be assumed, rather than being an interesting subject for comment.

C) Cognitive processes

This category includes three themes that describe cognitive aspects of the programming task, rather than notational elements. Classification decisions for these themes were conservative: a statement saying that visual languages were easier to read, for example, is classified as a statement about the notation rather than about the cognitive processes involved in reading. The category is divided into three themes: the first deals with perception of visual languages, and short term visual memory. The second includes descriptions of mental models in visual terms, and the third includes questions of affect.

C.1) Perception and memory

The statements central to this theme claim that VPLs take better advantage of the visual sensory modality than do textual languages. It is observed that the human mind is "optimised" for vision[29,14], making shapes easier to process than words[22,16]. Many of these statements refer to mental processes in specifically computational terms. In computer science research, image processing algorithms are often implemented using parallel computer architectures, whereas language parsing algorithms seldom are. Some computer scientists appear to draw a direct analogy to human cognition, saying that vision makes the fullest use of the parallel computational architecture of the human brain[29,18,27]. Similar analogies are drawn in descriptions of visual memory. Visual percepts are considered to provide a superior basis for mnemonic chunking, because an entire image as treated as a "single unit" by the brain, thereby providing a high communication bandwidth when compared to words, which must be recognised one at a time[18]. Although it must be a tempting speculation, only a few writers suggest that VPLs employ right hemisphere resources while textual programming languages employ left hemisphere linguistic resources[34]. Perhaps increased popular awareness of functional localisation in neuroscience may cause such speculation to be more common in the VPL literature in future.

C.2) Mental models

Statements were assigned to theme C.1 when they referred to cognitive processes involved in perception of visual languages. A number of statements considered the process of generating new programs, starting from the premise that the mental model of the program might already be in a visual rather than a linguistic form[5] – an introspection that is also reported by expert programmers (Petre & Blackwell 1997). A VPL might therefore represent this visual mental

model better than text can[28]. If there is a "semantic gap" between the programmer's conceptual model of what their program should do, and the computational model of the program itself[31], this gap can be "bridged" because the VPL depicts concepts directly[4,36]. This discussion is obviously related to theme B.3 (syntax reduction), but statements were assigned to the current theme where they expressly described the nature of the mental model.

C.3) Preference and affect

Many of the respondents in survey 3 simply stated that the VPL they used was more fun than textual equivalents. This is a perfectly good reason to choose a programming language, and may directly facilitate improved performance (Petre, Blackwell & Green 1998). Publications in the visual programming literature note that visual programming is more satisfying[17], appealing[24] or alluring[27] than text, which is time consuming, frustrating and labour-intensive[34]. The spirit of the advertising slogan "a picture is worth a thousand words" may be better captured by statements of attitude than of information content – these research publications observe the visual bias of modern society, in which people generally prefer pictures to words[35], motion pictures to books[37], and graphs to tables[18].

D) Metaphorical comparisons

This category contains themes with a direct bearing on the discussion of chapter 1. These authors are of course familiar with the desktop metaphor, and with the school of HCI research that teaches the importance of metaphorical interfaces. It is divided into three themes: the first refers to the analogical processes through which we can understand computers by relating them to our experience of the real world. The second refers to the claims of conceptual metaphor, that we understand abstractions in terms of concrete physical experience. The third refers to the metaphors of communication by which we compare human-computer interaction to natural language and conversation.

D.1) Applying real world experience

As in other HCI contexts, direct manipulation interfaces are a valuable aspect of a VPL. The reasons why this might be so are described in different ways, however. It is unlikely that icons are more "intuitively meaningful"[7] than words for many programming constructs, but Larkin and Simon's (1987) description of location as a coding mechanism (one which avoids hidden dependencies in reasonably small, planar diagrams) is echoed by these responses[10]. Direct manipulation employs manipulation skills based on ordinary actions in the physical world[10,27], but VPLs also use metaphors based on more specialised experience. Technical specialists in many fields choose to draw diagrams in order to help them understand complex situations[13]. Reference is made to the standard diagram forms used by software engineers as being "familiar"[31], or even "traditional"[24]. Perhaps other graphical representations such as

musical scores, recipe books and construction schedules[37] could also be used directly as metaphors for programming.

D.2) Making the abstract concrete

Several of these extracts stated that people find it easier to deal with the concrete than the abstract[5], and that solutions are easier to perceive if abstract information is converted to a concrete (i.e. visual) form[13]. This may simply be reflecting an extension of the principle of direct manipulation, but more detailed cognitive theories are advanced, for example that abstract mental models are more easily processed in well structured problems, but that concrete models are better for semi-structured problems[21]. This sense of abstraction as distinct from concrete representations has been separated in the theme classification from level of abstraction, which is usually used in a more specialised sense by computer scientists (and is included in B.5).

D.3) Comparisons to natural language

The high-level contextual metaphor of user interface as a dialogue between the user and the machine is even more seductive when programming – where the form of interface is described as a "language". Programming languages are often compared to human language, as are the visual languages considered in this survey[19]. Visual languages are, of course, far less like human language than earlier computer languages such as COBOL, but this has not prevented attempts to extend the metaphor. Some passages found in this survey suggest that people have always found it natural to communicate with images[27], that pictures are a universal form of communication[35], and that VPLs will transcend language barriers and allow exchange of programs between different nations[37] (although the vocabulary must first be designed not to be culture-specific[33]). Support for these arguments comes from some interesting sources – although some writers observe that written languages have evolved from hieroglyphics to more advanced modern forms[26], others suggest that logographic scripts such as Chinese are superior to the scripts of Indo-European languages which are constrained by the need to follow phonetic structures[11].

E) Miscellaneous observations

A few statements in surveys 2 and 3 could not be assigned to any of the themes described above, either because they could not be interpreted, or because they expressed a unique opinion that did not touch on any of the defined themes. These are not analysed in further detail.

Results

Each statement was allocated to one of the themes, and classified as to whether it drew a negative or positive conclusion about VPLs within the terms of the theme. (Statements could also be classified as equivocal or ambiguous). Note that the tallies reported below count the number of respondents addressing each theme, not the total number of statements. If one respondent made multiple statements on the same theme, this contributed a count of one to the tally. If a respondent made both positive and negative statements on the same theme however, this would contribute to both tallies. Figure 3.2 illustrates the distribution of statements among the themes in survey 1.

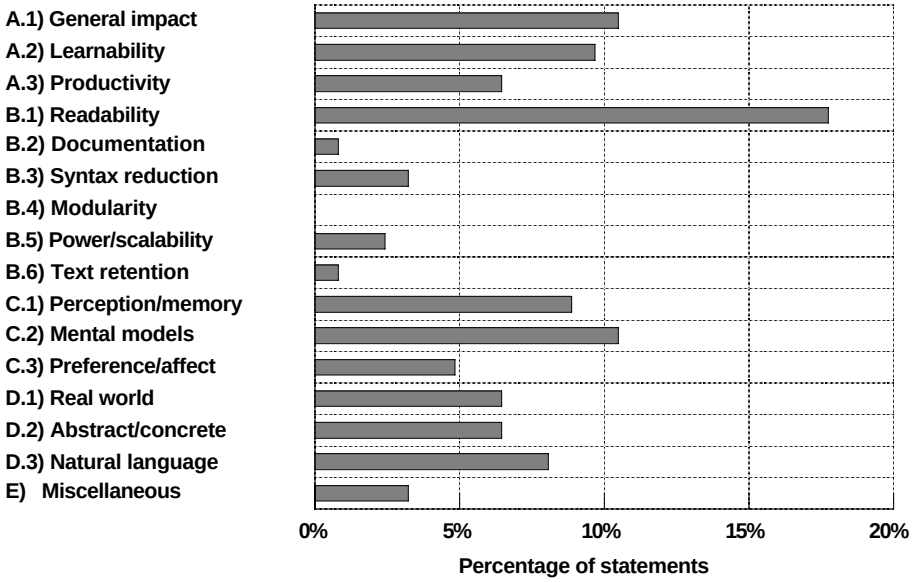


Figure 3.2. Distribution of statements between themes in survey 1

This distribution is compared to surveys 2 and 3 below. The proportion of statements found in each theme was very different in each survey, as was the proportion of positive and negative statements; figure 3.6 will show that the statements found in research publications included very few negative statements regarding any aspect of VPL use.

The classification category containing the largest total number of statements across several themes was category A (contextual significance) – that VPLs would have a positive general impact, producing improvements in productivity while also being easy to learn.

The theme receiving most attention overall was that of readability – this is obviously seen as a fundamental reason for introducing visual programming. Other notational properties

(category B) are not emphasised to the same extent, especially where they describe features that VPLs share with other programming languages (modularity, for example). Notational characteristics that affect program writing, such as syntax reduction, also receive less attention.

Statements regarding category C (cognitive effects of VPL use) include substantial numbers addressing all three themes. Mental models and perception/memory are particularly frequent, with levels of attention similar to those devoted to learnability and general impact. The three themes within category D, metaphorical correspondences between VPLs and previous experience, abstraction, and natural language receive approximately equal amounts of attention.

These themes are considered in more detail when contrasted with surveys 2 and 3 later in this chapter.

Discussion

The number of non-specific statements that are made about the general advantages of visual programming can be seen as a quantitative estimate of the predominance in the VPL literature of superlativism, as defined by Green, Petre and Bellamy (1991). This type of statement may also occur in other scientific disciplines – wherever it is necessary to describe the significance of research in general terms, even if the research itself is not applied. It is a matter for concern, however, where claims are made with no empirical support, when they could have been tested empirically. This is particularly true of the claims for learnability of VPLs – learning effects could be evaluated experimentally, but this has not been done in the publications surveyed.

Across the three surveys, a relatively wide range of themes addressed the notational properties of VPLs when compared to textual languages. This is an important comparison to make – Green's work on cognitive dimensions (Green 1989, Green & Petre 1996) has demonstrated the profound influence that notational structure can have on the ability to perform different cognitive tasks. In this survey, however, one type of task is addressed more often than all others. Despite the fact that reading a computer program is rather less demanding than writing or modifying one, it is the readability of VPLs that attracts most attention here. The reasons for that imbalance will not be addressed in the rest of this thesis, but the possibilities are worth considering. It is not that researchers are unaware of the need to write programs as well as read them: the themes in categories C and D address issues related to program writing. It is possible that improving readability is considered to be a more fundamental or tractable research issue than writability – either because writability is little affected by the language used, or because writing a program requires that the author continually read the code being

generated (Green's *parsing-gnisrap* model – Green, Bellamy & Parker 1987). Alternatively, researchers may suspect that VPLs are less writable than textual languages, but choose not to comment on this in their publications. There is some evidence for this latter possibility in the statements made by professional users of a VPL in survey 3.

The themes in category C include most of the more explicitly metacognitive statements found in this survey about mental processing of visual languages. These statements are very much statements of psychological theory, but psychological research is almost never cited in their support. What is their status, in that case? They include a consistent range of arguments, and could be described as a theory of *naive psychology* (Hayes 1985) analogous to McCloskey's (1983) observations of naive models of physical phenomena. The population under consideration in this survey have a rather unusual basis for their psychological theories, however – as computer scientists, their simulation of mental processes (Gordon 1986) may be influenced by their experience of computers, just as Watt (1997) suggests that non-programmers understand computers on the basis of anthropocentric psychological models. Computational metaphors of mind do occasionally appear in the literature on reasoning with diagrams (e.g. Waisel, Wallace and Willemain's (1997) description of Johnson-Laird's mental models as "analogous to a Structured Query Language database"), but the statements found in this survey tend to be less precise. This is particularly notable in the statements describing human cognition in terms of "bandwidth", "efficiency" or "parallel processing". When computer scientists speak of cognition, they may be unduly influenced by the nature of their work, as claimed by Roszak:

> *[The computer] brings with it certain deep assumptions about the nature of mentality. Embodied in the machine there is an idea of what the mind is and how it works. The idea is there because scientists who purport to understand cognition and intelligence have put it there ... The subliminal lesson that is being taught whenever the computer is used (unless a careful effort is made to offset that effect) is the data processing model of the mind.*
>
> Roszak (1986), pp. 245,246

The metacognitive models found in this survey are not derived solely from observations of computers, however. The terminology used in some of the publications does indicate origins in psychological research – use of the term "chunking", for example[18]. It is possible that many of these statements can be traced to the earliest research into visual programming, which was directly motivated by the same cognitive theories that have been influential in HCI. Chapter 3 considered the influence of Smith's theory of metaphor as a tool for manipulating abstraction in graphical user interfaces (Smith 1996). The PYGMALION system that he developed to express those theories (Smith 1977) was not only one of the earliest graphical user interfaces, however, but one of the earliest VPLs. Popular descriptions of his work on the Xerox Star (Smith, Irby, Kimball & Harslem 1982, Smith, Irby, Kimball, Verplank & Harslem

1982, Johnson, Roberts et. al. 1989) may be partly responsible for broad dissemination of his theories of mental representation, visual short-term memory, creative use of mental images, and other related topics – his book cites the sources of these psychological theories, but few of those that follow him do so.

Survey 2: Professional users of conventional programming languages

This second survey was designed to answer the main question raised by the first. Are the metacognitive beliefs expressed by VPL researchers commonplace among computer programmers, or do they simply reflect the research traditions of the VPL academic community? In order to answer this, I selected a survey population who were unlikely to have been exposed to the research literature on VPLs, but who were both familiar with computer programming and accustomed to comparisons of different programming languages and techniques.

The results of this study have previously been published in Blackwell (1996c).

Population

This survey was conducted at a trade show organised by a computer magazine – the EXE Developer's Show – held in London on June 15-16, 1995. The nature of the magazine gives some insight into the survey population. *EXE Magazine* is a popular British programming magazine, similar to (but with a smaller circulation than) the American publications *American Programmer* or *Dr. Dobb's Journal* – it contains a mixture of opinion columns and educational articles and is widely read by professional programmers, as well as by knowledgeable hobbyist programmers. It does not publish academic papers, but would discuss topics such as visual programming in the context of a product review. Such reviews would normally be based on manufacturer's press releases rather than academic analyses, however. Readers of the magazine might therefore have some awareness of new commercial trends in programming languages, but would probably not have encountered the cognitive theories motivating VPL research. Although there was a small conference associated with the show, the speakers addressed commercial issues rather than scientific ones – a programmer with a strong interest in programming language research would have chosen to attend one of the many more technical conferences held in London in 1995, rather than this one.

Method

The survey was conducted using a written questionnaire, reproduced in Appendix A. It started with two qualifying questions. The first question tested whether the respondents were professional programmers, as expected by the trade show organisers. The title and the second introductory question were worded in order to avoid confusion between VPLs and the Microsoft *Visual Basic* and *Visual C++* products (which would have been very familiar to most respondents). The body of the questionnaire consistently used the term 'graphical programming' rather than 'visual programming', and the second introductory question explained this as follows:

> *Do you have any experience of a graphical programming language, where the programmer does almost all programming by manipulating diagrams instead of typing text? Please note that this definition does not include tools like Visual Basic, where the program logic is created using a text language.*

In order to ensure that the point about Visual Basic had been assimilated, respondents were asked to name a VPL that they had used, seen or read about.

The third question asked respondents to compare a graphical and a textual programming language along five different dimensions: ease of use, power, enjoyability, readability and changeability. They were asked to name the text language they were comparing, and to either name a graphical language or write "guess" if they did not know the name of one. Two Likert scales were provided for each dimension, so that the respondent made separate assessments of graphical and textual languages on each dimension. The extremes of the scales were labelled separately, as follows: "hard to write/easy to write", "weak/powerful", "irritating/enjoyable", "unreadable/readable", "hard to change/easy to change". A further three unlabelled scales were provided, so that respondents could make comparisons on other dimensions that they might consider to be important. A differential response was encouraged by using six point scales, with no mid-point.

The final question was designed to elicit statements about the cognitive nature of the programming task, as investigated in survey 1. It read:

> *Please explain in a few sentences how you think a graphical programming language might make a difference to the "brain-work" involved in programming.*

The responses to this final question were analysed using the same coding frame that was described under the heading of survey 1. As for survey 1, an initial analysis of the results was published before survey 3 was carried out (Blackwell 1996c). The results reported here are based on the single coding frame that was formulated later to encompass surveys 1, 2 and 3 (Whitley & Blackwell 1997). The results that are presented in the following section are

therefore organised according to the same structure of themes and categories that was described earlier.

Results

The number of people attending the EXE Developer's Show was somewhat less than 1000 people (the organisers did not release exact figures). I distributed 506 questionnaires to visitors as they arrived at the show, and 88 of these were returned, either to a collection point on one of the exhibition stands, or by post afterwards.

According to their answers to Question 1, all but two of the respondents (98%) were professional programmers. This is as expected from the target readership of *EXE Magazine*.

Despite the instructions given in Question 2, 25% of the respondents did name Visual Basic (or a similar product) as the VPL that they were familiar with. This is a severe difficulty when surveying opinions about novel programming languages. Although the questionnaire never used the word "visual" and explicitly excluded Visual Basic, respondents who were unfamiliar with visual programming tended to respond confidently, but by reference to languages that they knew. The responses were divided into three groups according to reported experience with VPLs. (Seven respondents did not complete this question).

Group I	had seen, or were familiar with, a VPL (N=23).
Group II	had no prior experience of VPLs (N=37).
Group III	named Visual Basic or a similar product as a VPL (N=21).

The three groups of respondents differed significantly in only some of the relative ratings that they assigned to text and graphical languages, as shown in figure 3.3.

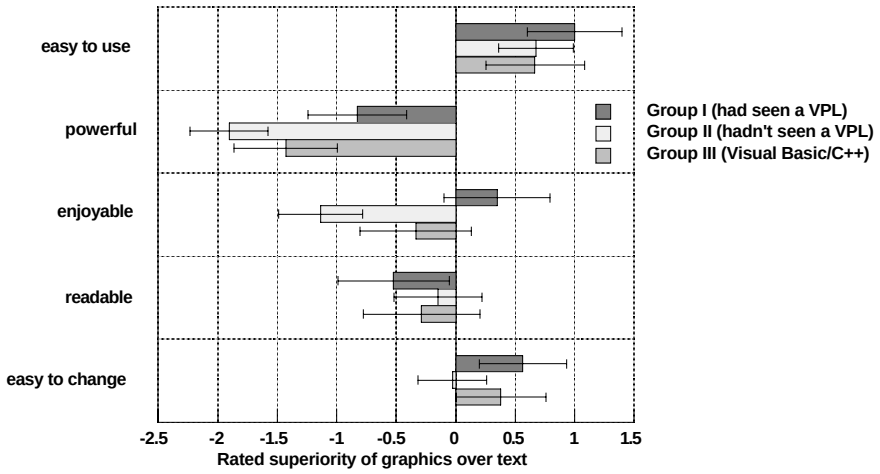


Figure 3.3. Mean rated advantage of graphical over text languages, sorted by VPL experience

All groups of respondents considered VPLs to be less powerful than text (the average rating for graphical languages was lower by 1.48 on the scale of 6), but easier to use (the average rating for graphical languages was higher by 0.77). The only scale for which there was a significant difference between the groups was the rating of whether graphical languages would be enjoyable to use. Group I gave graphical languages a slightly higher rating on this scale (by 0.35 out of 6), while groups II and III gave graphical languages lower ratings: by 1.14 and 0.33 respectively, $F(2,78)=3.51$, $p<.05$. When the independence of the different rating scales was compared, the strongest correlations (both positive) were found between the ratings of power and enjoyability ($r=.55$, $p<.001$), and between readability and changeability ($r=.53$, $p<.001$).

Although a significant difference was observed between some of the ratings given by different groups within the sample, a quantitative comparison of the number of positive and negative statements made in response to the open question found no significant difference between the three groups, $\chi^2(2, N=6)=0.69$, $p=.71$. The statements made by respondents to this survey are therefore considered as a single group when comparing them to those made by VPL researchers (survey 1) and professional VPL users (survey 3). The following discussion describes the differences in emphasis that were found within each coding theme for this survey. The variation in distribution of statements between surveys 1 and 2 is shown in figure 3.4.

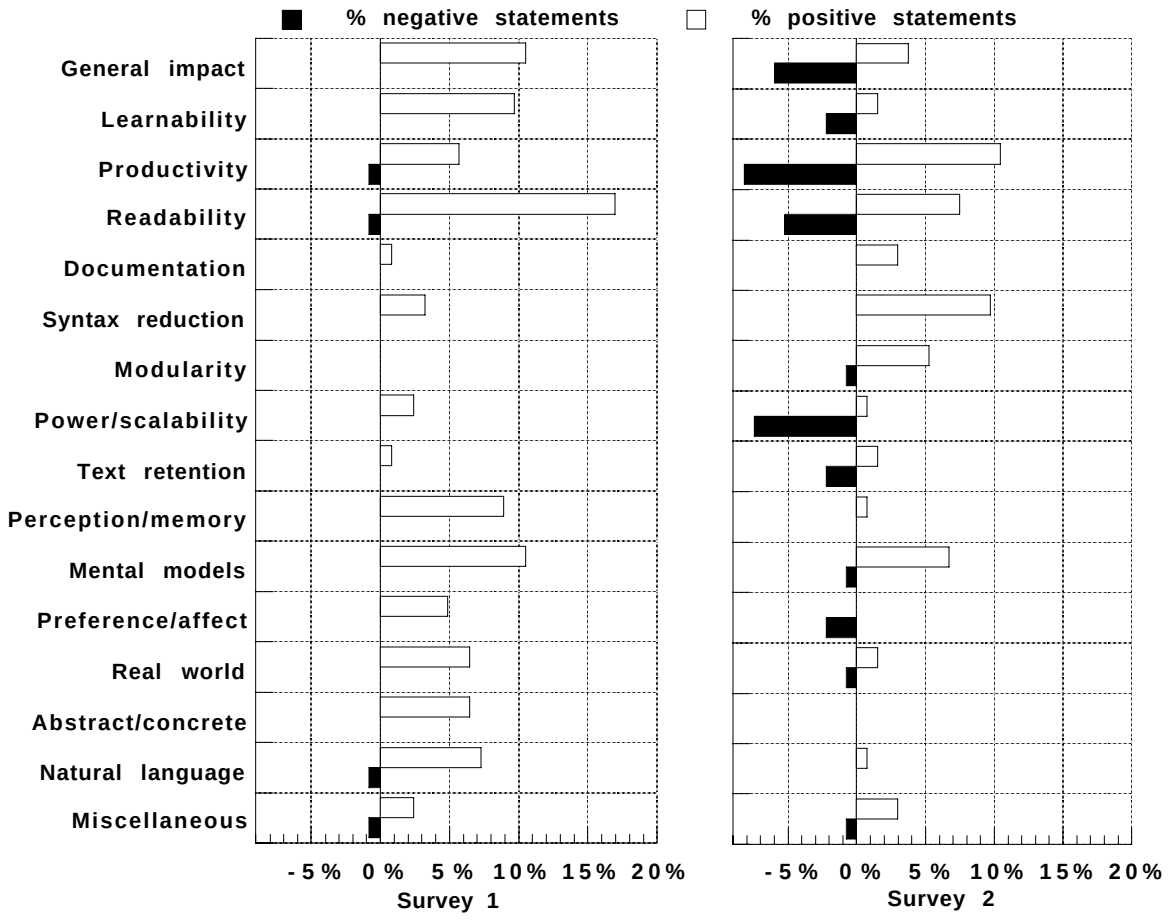


Figure 3.4. Theme distributions in surveys 1 and 2 – % of total statements in each survey

A) Contextual significance

Respondents in this survey were more likely to describe VPLs as having limited applicability, or only being appropriate for use in certain contexts.

A.1) General impact

Where VPL researchers often made superlativist claims regarding the benefits of VPLs, programmers in this survey were more cautious about the advantages. They were also readier to impute practical disadvantages to VPLs, including increased effort, reduced quality, or difficulty of maintenance. The motivation for this hostility might be partly explained by the concern expressed by some respondents that the ultimate objective of VPLs was to make professional programmers redundant by allowing other employees of a company to do programming work.

A.2) **Learnability**

Whereas VPL researchers often claimed that VPLs are naturally intuitive, the only professional programmer who mentioned intuition stated that VPLs were *less* intuitive than text.

A.3) **Productivity**

Professional programmers generally accord greater importance to productivity than to ease of learning. Responses to this survey considered that VPLs were intended for casual users, with a shallow learning curve that limits productivity.

B) **Notational characteristics**

Some respondents, having used many different programming languages, considered that their work is little affected by the language that they use. They observed that all languages are equivalent in their computational potential, and apparently have no regard for the cognitive ergonomics of the notation they used. Nevertheless, many respondents did make statements on notational issues.

B.1) **Readability**

Some respondents to this survey did agree with VPL researchers that VPLs can clarify relationships within a program. Many also expressed reservations about whether visual programs would scale up to large programs, or could contain more complex information.

B.2) **Documentation**

Where documentation was mentioned, respondents considered that a VPL would be beneficial, because easier to read.

B.3) **Syntax reduction**

While researchers proposed that VPLs allow direct manipulation of semantic information without syntax, programmers did not describe them in these terms. They did say that the programmer may be better able to concentrate on design and functionality rather than coding. This view was also commonly found in survey 3, and it interacts with theme C.2, which proposes that the suitability of the VPL for design tasks arises because of a resemblance to the mental model of the programmer.

B.4) **Modularity**

Many respondents were particularly concerned with the principles of structured design, stating that VPLs might encourage modularisation, decomposition, assembly of software components or object-orientation. All of these are topics that were of common concern in the industry at the time the survey was conducted, and might have been attributed to any new product.

B.5) **Power and scalability**

The tone of statements addressing this theme was divided: 33 respondents made positive comments regarding the power of VPLs, while 40 were sceptical or completely negative. Many limitations were mentioned, including that VPLs did not allow direct access to the machine, that large programs exceeded or cluttered the view area, or that program functionality is fragmented and obscured by event-driven code.

B.6) **Retention of text**

Several respondents pointed out that VPLs still require typing; for names, expressions, or component customisation.

C) **Cognitive processes**

Question 4 in the survey explicitly asked respondents to comment on the brain work involved in programming. This should have produced a strong bias toward the type of statements found in survey 1 on the themes related to cognitive processes. Despite this encouragement, respondents in survey 2 made proportionally fewer statements on these themes than were found in survey 1.

C.1) **Perception and memory**

Some programmers proposed that VPLs might reduce cognitive load, freeing the programmer to think about other problems. No statements were made about perceptual resources or working memory.

C.2) **Mental models**

Several programmers did describe VPLs as corresponding to their mental models. As in surveys 1 and 3, some respondents said that VPLs could directly express ideas – a property described in one case as ‘direct stimulation of the brain’.

C.3) **Preference and affect**

As noted earlier, groups II and III (who had no experience of VPLs) were more likely than group I to give a poor rating to the enjoyability of visual programming. This is borne out in responses to this open question. Where researchers stated that a major benefit of VPLs would be programmer’s enjoyment in using them, a number of respondents in survey 2 objected that VPLs would reduce the quality of their work, make maintenance more difficult, waste their time, and reduce the intellectual challenge in their work.

D) **Metaphorical comparisons**

Do the statements made by VPL researchers about the value of metaphor reflect a general belief among professional computer users, or are they specific to the research community, perhaps due to the influence of only a few publications, as suggested in the analysis of survey 1?

D.1) **Applying real world experience**

Respondents in this survey never observed that VPLs might resemble the real world. They did make some comments about the use of direct manipulation interfaces, but these were often negative – objecting that icons were hard to remember and manipulate. Group III respondents were positive about the general benefits of graphical user interfaces, but this is unsurprising, given that for Visual Basic/C++ programmers, the creation of graphical user interfaces is their livelihood.

D.2) **Making the abstract concrete**

Where VPL researchers stated that people find it easier to deal with the concrete than the abstract, and that solutions are easier to perceive if abstractions are converted to a visual form, some programmers mentioned that the use of diagrams can restrict the development of abstractions.

D.3) **Comparisons to natural language**

One respondent in group III did echo the ambitions of VPL researchers, that VPLs might help to cross language barriers by being less dependent on English. As a Visual Basic/C++ user, this concern was probably derived from the emphasis on internationalisation in those tools.

E) **Miscellaneous observations**

A few respondents made comments relevant to only one product. These were not analysed any further.

Discussion

The assessments made by respondents in this survey can be reasonably summarised by the relative ratings they made of VPLs and textual programming languages on Likert scales. The attitude towards VPLs was generally sceptical, and even hostile in some respects. This was true for each of the three groups identified in the sample, although respondents who had at least seen a VPL were more likely to be charitable, particularly in perceiving VPLs as being enjoyable to use – the same attitude is observed on a larger scale in survey 3. It is notable that Group II, with no experience at all of VPLs, were completely convinced that they would be unpleasant to use. This type of response is consistent with other studies of professional computer users, which find that their attitudes to their tools are often a matter of vigorous allegiance – this effect is strongest when the new tool is substantially different to the old, as in the case of the Macintosh (Jones 1990).

This attitude appears to be linked to the niche that VPLs are considered to fill in the spectrum of software tools. Respondents expressed the main advantage of VPLs as being that they were

easy to use. This ease of use is thought to be achieved to the detriment of the tool's power, however. For these professional tool users, it is the power of the tool that is most strongly correlated with their assessment of whether they would enjoy using it – this correlation will be seen again in survey 3.

The responses to the open question follow the same broad pattern of opinion. VPLs are described as easy to use in some respects, but deficient in many aspects important to professional programmers. The general impact of VPLs (category A) is defined by the fact that they are designed for casual users, but at the expense of reduced productivity. They even threaten the livelihood of professional programmers, by encouraging non-professionals to meddle with programming.

Statements made about the notational advantages of VPLs (category B) were generally realistic, indicating that programmers have some appreciation of the characteristics described by Green's Cognitive Dimensions. Rather than appealing to intuition, it is more reasonable to attribute the advantages of a visual representation to the fact that it clarifies relationships, and expresses functionality in a way less obscured by typographical syntax. This advantage is offset by the fact that the visual representation may allow a more limited repertoire of expression, or may not scale up to the description of larger systems.

Despite the fact that the open question specifically asked respondents to speculate about the cognitive processes involved in programming, most of them restricted their comments to aspects of programming with which they were familiar – the notation itself, and the context in which it is used. The proportion of statements describing cognitive processes (category C) and the use of metaphor (category D) was far lower than had been found in survey 1. The few respondents who did mention these issues seemed to do so on the basis of some familiarity with HCI research (for example, in referring to cognitive load). The one exception in these categories was theme C.2 - mental models. Of those respondents who made any statement about cognitive issues, the great majority described visual representations as corresponding to the mental model they had of the design. This is in accordance with the introspective statements found by Petre and Blackwell (1997) in their analysis of expert programmers' descriptions of mental imagery. The respondents in this survey did not elaborate their descriptions, so it is not possible to tell whether they are referring to the complex images described by Petre and Blackwell, or simpler representations such as flowcharts – further evidence on this question was found in survey 3.

Survey 3: Users of a visual programming language

A large difference was found between the opinions expressed in surveys 1 & 2. This result does not give any support to the hypothesis proposed in the analysis of survey 1 – that there are widespread and consistent metacognitive theories of naive psychology regarding the way that programmers use visual representations. The responses in survey 2 appeared to be heavily biased, however, by the hostility that the respondents expressed toward VPLs. It may be the case that survey 2 respondents have similar metacognitive theories to VPL researchers, but they chose not to express them, concentrating instead on negative aspects of VPLs. In order to test this, a further survey was made of experienced users of visual languages

This study was used to collect data for two relatively independent projects – the second project being an investigation of the computational advantages of LabVIEW, conducted by Vanderbilt University PhD student Kirsten Whitley. It has previously been published by Whitley and Blackwell (1997).

The population of survey 3 were users of LabVIEW (Laboratory Virtual Instrument Engineering Workbench), a programming environment marketed by National Instruments for development of data acquisition, analysis, display and control applications. LabVIEW features a dataflow-based VPL, called G, which is promoted as being usable by scientists and engineers having limited programming experience, but who need to write software to interact with laboratory equipment. LabVIEW has been commercially available for 10 years, and has enjoyed relatively wide success compared to other VPLs, the majority of which are research prototypes. It is therefore an ideal candidate for studying a VPL with a sizable population of experienced users.

There have also been previous empirical studies of LabVIEW. Baroth and Hartsough (1995) describe the experience of their company using VPLs. In one case study they compared the progress of two development teams, one using LabVIEW and the other using the textual language C. The teams developed systems concurrently, to the same specification. After three months, the C team had not yet achieved the specification, while the LabVIEW team had exceeded it. On the basis of this and other studies, Baroth and Hartsough report that LabVIEW projects are 4 to 10 times faster than those using a textual programming language. They attribute this superiority to the fact that VPLs are easier to read, and that the style of LabVIEW makes it familiar to the electronics engineers in their company. In contrast, an experimental study by Green, Petre and Bellamy (1991) revealed no performance benefits resulting from LabVIEW's visual notations for conditional logic. In fact, their sample of

experienced LabVIEW users and electronic designers were uniformly faster at interpreting conditional logic written in a textual language than in LabVIEW.

The clarification of these apparently contradictory findings was one of the main concerns in the design of survey 3. It is possible that Baroth and Hartsough were incorrect in attributing performance improvements to LabVIEW's visual notation. It may be that LabVIEW does improve programming but that the cause of the improvement stems from language features other than the visual syntax. These issues are the concern of Whitley's project (Whitley 1997), and are described by Whitley and Blackwell (1997, 1998). Those parts of survey 3 which relate to Whitley's project are not described in any further detail in the current discussion.

Population

The respondents in this survey were recruited from two sources of LabVIEW users. The main source was *info-labview*, a mailing list for LabVIEW programmers. As of January, 1997, *info-labview* had approximately 2,300 subscribers. The second source was an email directory, compiled by National Instruments, of academic users of LabVIEW. We sent invitations to participate to 104 addresses from this directory. The third source was readers of the Internet newsgroup *comp.lang.visual*. National Instruments also created a link to our survey from their home page on the World Wide Web.

Method

This survey was administered electronically in two versions: an HTML form accessible via the World Wide Web, and an e-mail form for which responses could be inserted between question texts. The majority of responses used the HTML version, which can be seen in Appendix A. When a response was submitted from the Web page, a program on our Web server (a cgi-script implemented in Perl) analysed the response, checking for complete answers. If the script detected missing information, it asked the respondent to fill in the missing information. This precaution resulted in a substantial increase in the number of complete responses.

The questionnaire was divided into four parts. The first requested information about the respondent's programming background. Question 1 asked for an email address (this was optional – in case clarification was needed – but was eventually used only to award incentive prizes supplied by National Instruments). Question 2, like the first question in survey 2, asked whether the respondents were professional programmers. Question 3 asked respondents to make a qualitative estimate of programming experience, in terms of the number and size of

projects completed in LabVIEW and in other languages. Question 4 asked respondents to name the programming language that they had had the most experience using.

The second part of the questionnaire elicited opinions about LabVIEW as a whole, without emphasizing its visual aspects. This part was exploratory, and included several open questions designed to invite comments about non-visual aspects of LabVIEW, if respondents considered those to be important. Questions 5, 7 and 8 asked respondents for their overall opinion of LabVIEW, examples of how LabVIEW makes programming easier, and examples of how LabVIEW makes programming difficult. Question 6 directly addressed Whitley's hypothesis regarding Baroth and Hartsough's observed productivity increases from LabVIEW use. It asked respondents to assess the relative importance of various LabVIEW features using a 6-point Likert scale. The visual language G was only one of these features – others included reusable libraries of LabVIEW code, data acquisition hardware, and user interface development facilities.

The third part of the questionnaire asked explicit questions about the visual aspects of LabVIEW (i.e. the VPL *G*), and was very similar to the questionnaire used in survey 2. In Question 9, respondents are asked to compare *G* along several dimensions against a textual programming language of their choice. The first five of the dimensions are identical to the dimensions used in survey 2: power, ease of use, readability, changeability and enjoyability. We also added two further dimensions specifically to address the findings of Green, Petre and Bellamy (1991) – these asked respondents to compare support in *G* for conditional logic (as tested by Green et. al) and repetitive logic. Finally, question 10 is identical to the final question in survey 2; it asks respondents to explain how and why the graphical nature of *G* affects the "brain-work" required in programming.

The coding frame used for open questions was described above in the discussion of survey 1, although the five theme categories described earlier only constitute half of the themes to which statements could be assigned in survey 3. A second hierarchy of themes dealt with non-visual aspects of LabVIEW, as described by Whitley and Blackwell (1998). Those themes are not discussed here. Although respondents were not asked specifically about the effect of using the graphical language until the end of the questionnaire, some respondents did choose to describe cognitive effects when answering the earlier questions. We therefore aggregated all responses to open questions, and coded them as referring to visual or non-visual aspects of LabVIEW according to the content of the response, rather than the context of the question being answered. This is consistent with the approach taken in survey 1, where metacognitive statements were found in contexts ostensibly describing questions of computer science rather than questions of psychology.

Results

The survey was advertised on 11 March 1997, and we received 227 complete responses by 1 April. The majority of respondents (132) were professional programmers, as in survey 2. Of the remainder, 75 said that programming was only part of their job, 14 were academics and 6 gave 'other' responses. No significant differences were found between these groups in their responses to any of the questions discussed below.

As expected, LabVIEW users held far more positive opinions about VPLs than the programmers questioned in survey 2. When the relative differences between the ratings given to text languages and LabVIEW were compared to the relative differences in survey 2, multivariate analysis of variance (MANOVA) indicates a significant difference across all five rating scales, $F(5,297)=0.317$, $p<.001$. The rating differences between the two surveys are illustrated in figure 3.5. LabVIEW programmers rated LabVIEW as superior to text in all respects, including those where survey 2 respondents thought that VPLs would be worse than text: power, readability and enjoyability, $t(305)=8.53$, $p<.001$, $t(306)=5.80$, $p<.001$ and $t(302)=8.18$, $p<.001$ respectively. Although survey 2 respondents considered VPLs less powerful than text, they did accept that VPLs might make programs easier to write. Survey 3 respondents also considered that LabVIEW improved ease of writing more than power, $t(225)=7.70$, $p<.001$. The relative size of this difference is greater in survey 2 than in survey 3 however, $t(305)=3.51$, $p<.001$. Both survey 2 and survey 3 respondents considered that VPLs facilitated writing programs more than reading them: $t(80)=3.95$, $p<.001$ and $t(226)=2.90$, $p<.005$ respectively.

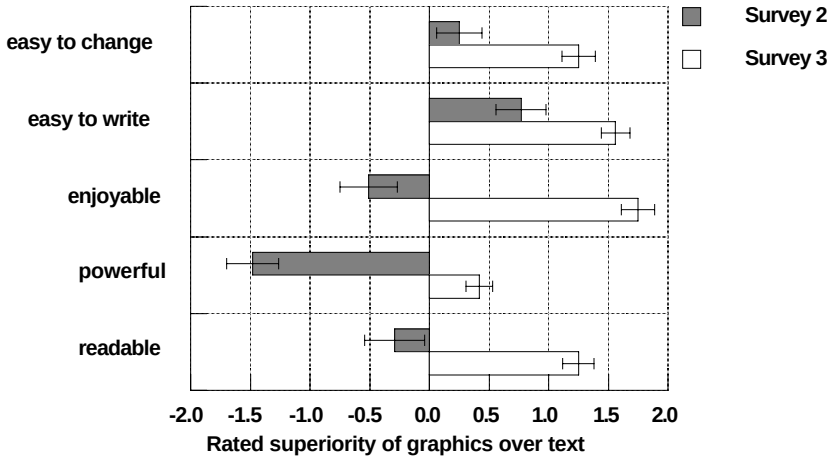


Figure 3.5. Relative ranking of text and VPL factors in surveys 2 and 3

In survey 2, the sub-group who had never encountered a VPL were found to be more negative in their opinions. A complementary effect was observed in this survey. Respondents who were not familiar with any textual programming language were instructed to enter "guess" when naming a textual language to compare to LabVIEW. The 21 respondents who did so gave significantly poorer ratings to textual languages than other survey 3 respondents, especially regarding the power of text relative to LabVIEW, $t(224)=4.68$, $p<.001$. As with survey 2, programmers who know little about a language are likely to have a poor opinion of how powerful it is. This hypothesis is supported by correlations between the amount of experience reported by respondents and the total rating marks given. The total rating given to LabVIEW was positively correlated with amount of LabVIEW experience, but there was no correlation with general programming experience, $r=.35$, $p<.001$. The reverse was true of total rating given to text which was only correlated with general experience, $r=.34$, $p<.001$. This suggests that programmers do not normally assess programming languages by critical generalisation from their experience of other languages, but rather by a switch of opinion from scepticism to comfort and familiarity.

One of the objectives of this survey was to find out whether LabVIEW programmers were aware of its weakness in expressing conditional logic, as observed by Green et al. (Green, Petre & Bellamy 1991; Green & Petre 1992). If so, they should give a lower rating to LabVIEW when comparing its conditional logic to text languages than they do when comparing repetition constructs. In fact, respondents' awareness of this issue depended on the amount of familiarity they had with textual languages. Those who entered "guess" in question 9 were significantly more positive than other respondents in their assessment of conditional logic in LabVIEW, $t(224)=2.76$, $p<.01$, but not in their assessment of repetition constructs. Similarly, respondents who reported having completed more projects with other languages than with LabVIEW generally gave a negative assessment of LabVIEW's conditional logic (poorer than text by 0.36), while the rest of the sample gave it a positive assessment (better than text by 0.39), $t(224)=3.13$, $p<.005$. These textually-experienced respondents gave a neutral assessment of LabVIEW's repetition constructs (the mean assessment differed only by 0.008 from that given to text languages).

The coding framework for responses to open format questions has been discussed in the presentation of surveys 1 and 2. The version of the framework described in this thesis was created to encompass all three surveys, however. In the case of survey 3, the sample was sufficiently large to allow a simple assessment of coding reliability between the two raters. One rater coded all responses, then the second rater coded a randomly selected 20% sample, excluding those responses that had been used when creating the coding framework. The codes assigned by the second rater agreed with the first in 92% of the statements.

The total proportion of negative and positive opinions found in survey 3 was intermediate between surveys 1 and 2, as shown in figure 3.6. Survey 3 respondents were more likely to be positive about VPLs than in survey 2, but less than in survey 1. They were more likely to be negative than survey 1, but less than survey 2. This is consistent with the assessments made on the rating scales of surveys 2 and 3. The following paragraphs compare the level of interest in each of the themes across the three surveys.

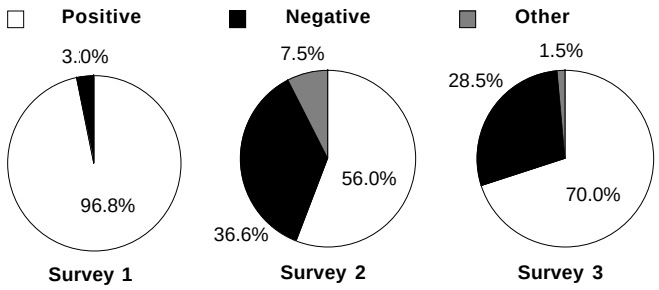


Figure 3.6. Proportion of positive and negative opinions expressed in each survey

A) **Contextual significance**

Figure 3.7 summarises the relative proportion of statements made on contextual significance themes in surveys 1, 2 and 3.

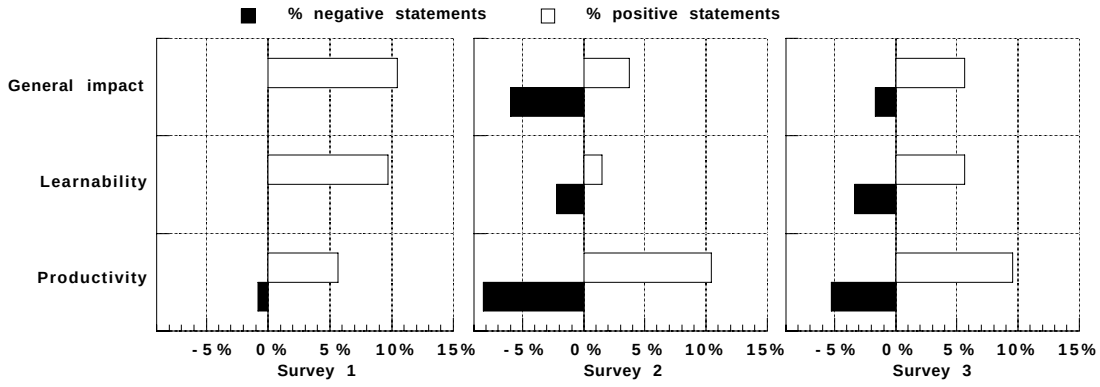


Figure 3.7. Attention to contextual themes in surveys 1, 2 and 3

A.1) **General impact**

As with statements found in survey 1, LabVIEW programmers often mentioned general ease of use as an advantage of VPLs. Survey 2 respondents more often stated that this goal would not be achieved – that VPLs would make no difference to users, or even be more difficult to use.

A.2) **Learnability**

Both VPL researchers and LabVIEW programmers cited ease of learning as a benefit of VPLs, where survey 2 respondents were more likely to criticise the time required to learn simplistic languages. LabVIEW programmers did express reservations about the difficulty of learning the dataflow paradigm of LabVIEW, which was very different to languages that they had used previously.

A.3) **Productivity**

LabVIEW programmers reported productivity benefits not only in coding, but in the design, debugging and maintenance phases of software development. The survey 2 programmers believed the reverse – that the advantages of visual programming would be found only during coding and that these other phases would see no change or even decreased productivity.

B) **Notational characteristics**

Figure 3.8. summarises the relative proportion of statements made on notational themes in surveys 1, 2 and 3.

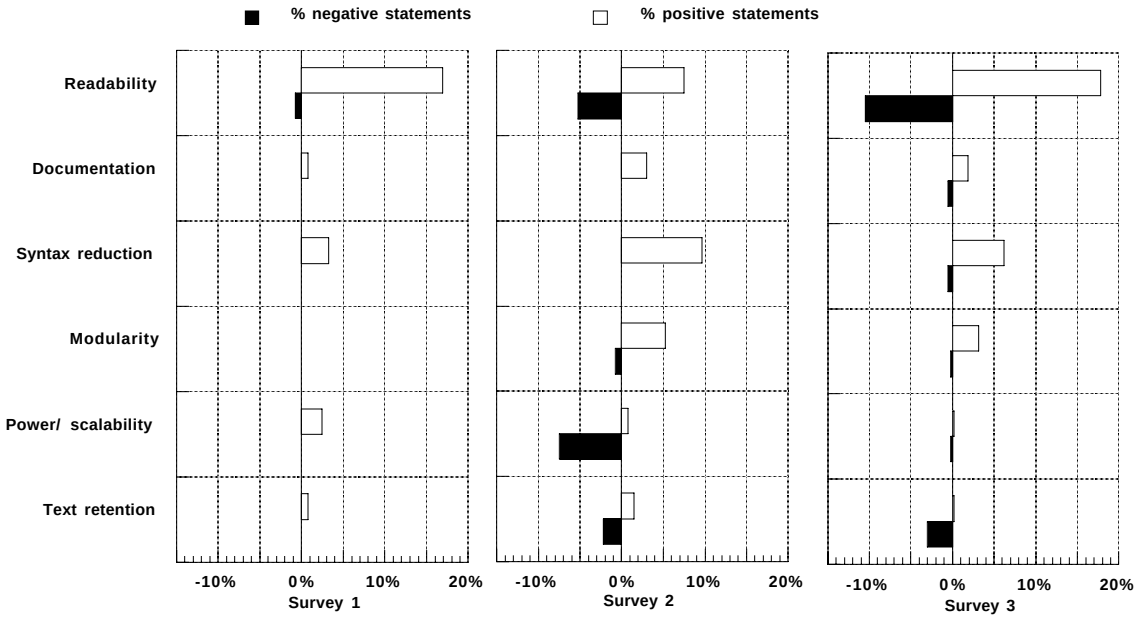


Figure 3.8. Attention to notational themes in surveys 1, 2 and 3

B.1) **Readability**

Respondents in all three surveys regularly noted that VPLs clarified the structure of a program. LabVIEW programmers were more likely than survey 1 or 2 respondents to discuss "Gestalt" views or the "big picture" of a program. They were also more likely to describe the negative aspects of LabVIEW's readability; complaining about messy, cluttered code – literally resembling "spaghetti".

B.2) **Documentation**

Only a few respondents in each survey referred specifically to the role that visual representations can play as a documentation and communication medium. Baroth and Hartsough's (1995) opinion that LabVIEW facilitates communication between programmers and their clients is not widely supported.

B.3) **Syntax reduction**

VPLs do mitigate the problem of minor syntax errors in programming, This aspect of VPLs was not often mentioned by VPL researchers, however. The professional programmers in

survey 2 and 3 were concerned with minimising syntax. In fact, two LabVIEW programmers complained about the novel syntactic demands in wiring up large programs.

B.4) **Modularity**

Survey 2 respondents mentioned modular programming more often than survey 3. This is not a major emphasis in LabVIEW, whereas survey 2 was conducted at a time when object-orientation was the main technical trend being adopted in commercial programming.

B.5) **Power and scalability**

Survey 2 respondents appeared concerned that high-level VPLs might deny them access to the low-level facilities of the machine that are so important in PC programming. This has often been a matter of concern with new generations of programming language, and it was most uniformly seen as a disadvantage by survey 2 respondents. Neither researchers nor LabVIEW programmers appeared as concerned.

B.6) **Retention of text**

A few survey 2 respondents seemed to find it hard to believe that an arbitrary computational operation could be represented graphically; stating that there would always be some level where the visual representation would be inadequate. This is not the case in LabVIEW.

C) **Cognitive processes**

Figure 3.9. summarises the relative proportion of statements made on cognitive process themes in surveys 1, 2 and 3.

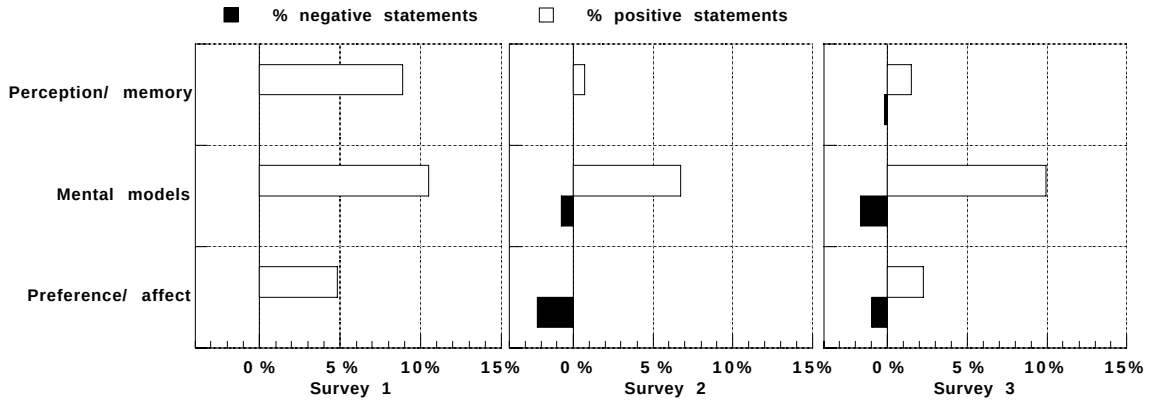


Figure 3.9. Attention to cognitive themes in surveys 1, 2 and 3

C.1) **Perception and memory**

Survey 3 respondents seldom mentioned perceptual processes. One respondent explicitly discounted the type of statement made in survey 1: "the human brain is massively parallel but basically operates in a linear fashion. *G* is parallel, but not in the least bit linear."

C.2) **Mental models**

As in surveys 1 and 2, LabVIEW programmers also stated that the designs they construct in their minds are in some sense pictorial or that VPLs are closer in nature to their thoughts than are textual languages. These opinions may be influenced by the predominance of diagrammatic notations in software design, but they are supported by the introspective evidence reported by Petre and Blackwell (1997).

C.3) **Preference and affect**

Survey 1 researchers stated that VPLs would be popular simply because people would enjoy using them. Several LabVIEW programmers said that they think using LabVIEW is fun, but the conservative coding policy followed in this survey meant that those statements were not interpreted as relating to the *G* language unless respondents explicitly said so – it may be the case that respondents consider the editing environment or the front panel assembly in LabView to be fun, rather than the *G* language.

D) **Metaphorical comparisons**

Figure 3.10. summarises the relative proportion of statements made on metaphorical comparison themes in surveys 1, 2 and 3.

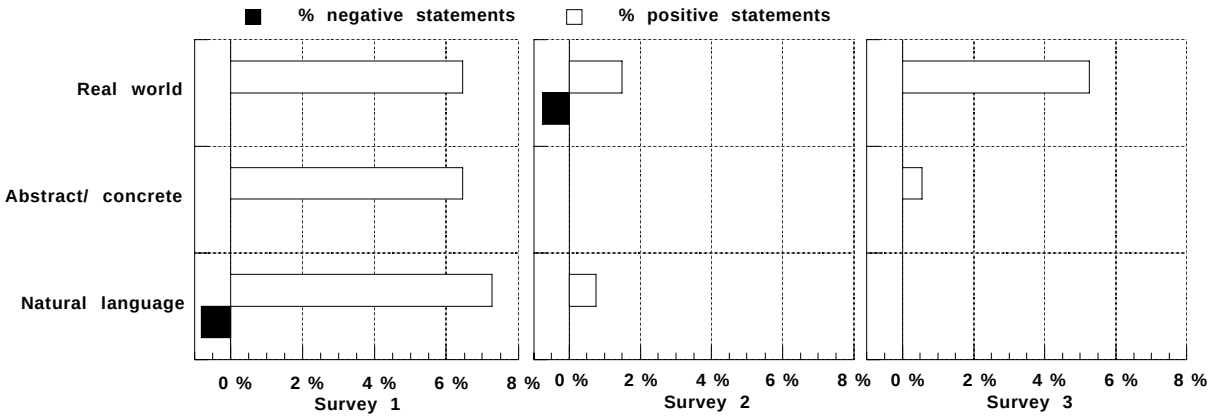


Figure 3.10. Attention to metaphorical themes in surveys 1, 2 and 3

D.1) Applying real world experience

LabVIEW exemplifies the principle of presenting abstraction in terms of real-world concepts that are already familiar to the programmer. Several LabVIEW users agreed that their previous experience in engineering or electronic circuit-building had been very important to them in learning the wiring metaphor that is central to LabVIEW.

D.2) Making the abstract concrete

The claim made by VPL researchers, that VPLs make abstract concepts easier to understand by presenting them in the form of concrete images, was hardly mentioned by respondents in either survey 2 or 3.

D.3) Comparisons to natural language

Survey 3 respondents seldom compared VPLs to human languages; a comparison that was found in survey 1.

E) Miscellaneous observations

In survey 3, some issues specific to LabVIEW were not compared directly to other surveys, despite the fact that they can be seen as general problems in VPLs – for example, the fact that it can be difficult to produce a paper print-out of a visual program. This type of issue may be a significant irritation to professional users of a VPL, but neither researchers nor non-VPL users would be likely to consider it.

Discussion

The results of this survey have emphasised the conservatism of professional programmers' opinions about their tools. In both surveys 2 and 3, respondents were most positive about the tools that they had most experience using. Their opinion of new techniques or unfamiliar languages was generally sceptical and even hostile. These opinions were often expressed confidently, but appear to be associated with lack of experience and understanding of the tools being discussed. The reasons for this attitude have not been investigated here, but there are several obvious candidates: the highly competitive market for software tools, the existence of support groups where programmers meet to reinforce their allegiance to specific languages, and the desire to protect one's professional specialist knowledge of existing tools, among other factors. In the context of these attitudes, it is not surprising that so many respondents in survey 2, rather than echoing the opinions of VPL researchers about the benefits of visual programming, denied that VPLs would bring any advantages at all. The balance of opinion was restored in survey 3, where, with much the same motivation, LabVIEW programmers were highly positive about VPLs and derided textual programming languages (especially if they had not used them).

In cases where the survey respondents analysed language facilities on a more critical basis, it seems that the area of improvement most interesting to professional programmers is facilities that might improve their productivity during mundane tasks. These improvements can be analysed in terms of relatively well-understood usability measures, especially Green's Cognitive Dimensions. Survey 3 respondents with experience of both VPL and text languages confirmed the finding of Green, Petre and Bellamy (1991) that experimental subjects are slower to interpret conditional logic in LabVIEW than in BASIC.

There are further observations made by respondents that have not yet been investigated empirically, and may be worthy of research. The VPL researchers in survey 1 appear to consider that the main advantage of visual representations is that they are easier to read. Respondents in both surveys 2 and 3, however, reported that the main contribution is that they are easier to write, with readability being relatively poor. A similar distinction between the appearance of comprehension and actual lack of understanding has also been found in studies of English text reading (Glenberg, Wilkinson & Epstein 1982). Another theme expressed in both surveys 2 and 3 is the perceived trade-off between power and usability in programming languages. There is no obvious theoretical reason why a powerful language should be difficult to use. It would be interesting to investigate whether this perception comes from the dichotomous marketing of programming tools in "student" or "end-user" versus "professional" categories, or whether the perceived trade-off arises from cognitive dimensions such as diffuseness and abstraction gradient.

Professional programmers, while aware of potential improvements in productivity from new languages, give little attention to the theories of cognition that are mentioned by so many VPL researchers as motivating the development of VPLs. The one topic in this area that is addressed regularly in all three surveys is the belief that programming involves the creation of image-like mental representations. This intuition is supported by in-depth interviews with expert programmers, as reported by Petre and Blackwell (1997). Despite this common intuition, it is not a necessary fact that the formation of image-like mental models will be facilitated by the use a diagrammatic external representation – what Scaife and Rogers (1996) call the *resemblance fallacy*. The relationship between mental imagery and diagrams motivates the first experiment to be discussed in chapter 3, and is investigated in considerable detail in chapter 4.

The hypothesis that VPLs are essentially metaphorical is seldom raised by the professional programmers of surveys 2 and 3. LabVIEW includes a quite specific metaphor – of programming as the creation of an electronic circuit (the cursor, when connecting components, resembles a spool of wire). Despite this emphasis, relatively few LabVIEW programmers mentioned it as an important benefit. If the idea of programming languages as

metaphors is not widespread amongst programmers, why is it so often mentioned by VPL researchers? The researchers do not cite specific sources, so it would appear that this metacognitive theory has been transmitted through the VPL research community by informal means, perhaps originating from Smith's (1977) description of visual programming as a "metaphor for thought". After completing the formal analysis of survey 1, and throughout this research project, I continued to find statements in the research literature making even more explicit claims about the relationship between abstraction, mental imagery and metaphor. These might easily have appeared in Smith's original publication. A typical example is:

> *Rather than forcing the programmer to make his concepts of how a system should work conform to a given programming language and environment, the environment and language should conform to the programmer's concepts. […] Attempting to have programmers directly [sic] with their conceptualizations has several interesting implications: The environment has to be graphical. People often think using pictures. Many of the conceptual views of programming are two-dimensional, graphical ones. The programmer must be able to work using the pictures that compose his conceptualizations and to assign meaning to these pictures.*
>
> Reiss (1987), p. 178

The remainder of the current thesis principally investigates this premise of VPL research. If the intuitive claims of VPL research are justified, and if Smith's original insights are supported by empirical evidence, then the use of metaphor must be treated far more seriously as a fundamental design principle for all types of diagram. The experiments in the next chapter and in chapter 5 undertake this investigation.

Chapter 4: Diagrammatic Metaphor in Instruction

The giving form and shape, to what otherwise would only have been an abstract idea, has, in many cases, been attended with much advantage.

The Commercial and Political Atlas
W. Playfair, 1801, p. xi.

The experiments reported in this chapter test the fundamental claim of the user interface metaphor, and one of the underlying assumptions of visual programming language advocates – that novel abstract concepts can be presented diagrammatically in terms of familiar physical experience. In the context of building user interfaces, it may be reasonable to claim that an interactive diagram imitates what Gibson (1979) called the perceptual affordances of the physical world. As in the physical world, graphical affordances indicate potential actions within the interface (Norman 1988, Larkin 1989). Affordances do not require explicit metaphor (Mohnkern 1997a), and may even fail if metaphors are drawn too far from their source domain (Lewis 1991). Theories of user interface affordances have often been conflated with the role of visual structure in forming analogies. This role was demonstrated in a more general investigation by Beveridge and Parkins (1987), showing that analogical solutions are more easily discovered when their structure is presented visually – but those findings have not been tested in user interface applications.

Many theories of diagrammatic reasoning claim, however, that knowledge of the physical world is used to interpret diagrams even when they do not support interaction. These are often related to theories of conceptual metaphor and thematic relations claiming that all abstractions, even linguistic ones, are derived from embodied experience (Jackendoff 1983, Johnson 1987, Lakoff 1987). Conceptual metaphor theories attract considerable debate, with theoretical and experimental evidence both for (Gibbs & O'Brien 1990, Gibbs 1996, De Vega, Rodrigo & Zimmer 1996) and against (Murphy 1996, 1997, McGlone 1996, Rumelhart 1993). Spatial representations are equally contentious when proposed as a cognitive basis for grammar (proposed by Talmy 1983, but challenged by Choi & Bowerman 1991) or for memory (proposed by Glenberg 1997, and sure to be challenged soon). Despite the disputed status of conceptual metaphor theories, HCI researchers such as Tauber (1987) and Hutchins (1989) argue that user interfaces similarly reflect spatial representations of abstract structure. Gattis & Holyoak (1996) make the same argument regarding the interpretation of Cartesian graphs. Lakoff (1993) has also extended his observations on the linguistic consequences of spatial experience to encompass the use of diagrams to express abstraction.

The experiments reported in this chapter address these claims by testing whether spatial representations, when used in the context of visual programming, do facilitate abstract problem-solving. Surveys 1 and 3 discovered a range of beliefs that appear similar in some ways to the claims about conceptual metaphor. In fact, programming is a far more complex activity than those that are used in typical metaphor experiments. Writing a computer program is a loosely constrained problem solving exercise rather than being like generation of natural language (Green 1980, Green, Bellamy & Parker 1987, Visser 1992, Koenemann & Robertson 1991). Many studies of problem solving have demonstrated the potential for using one or more external representations as a cognitive tool (Katona 1940, Schwartz 1971, Carroll, Thomas & Malhotra 1980, Anderson 1996, Cox 1997, Zhang 1997). In solving programming problems, the language acts both as the solution medium and the problem solving representation. A visual programming language must therefore be effective as a diagrammatic tool for problem solving.

The two experiments in this chapter compare the effect of metaphor in the representation to the effect of programming expertise. Many studies have observed that expertise in using a specific notation has a significant effect on both problem-solving strategies and performance, in fields including not only programming (Adelson 1981, McKeithen et. al. 1981) but electronic circuit design (Egan & Schwartz 1979, Petre & Green 1993), meteorology (Lowe 1993b), abacus use (Hishitani 1990) and blindfold chess (Saariluoma & Kalakoski 1997).

Visual programming languages, however, are not primarily designed for use by expert programmers. Graphical representations are expected to be more appropriate for inexperienced computer users (van der Veer, van Beek & Cruts 1987, Sohn & Doane 1997), and the value of visual programming languages for inexperienced users has been demonstrated in studies by Cunniff & Taylor (1987) and Mendelsohn, Green & Brna (1990), as well as being an explicit claim when programming languages are promoted for use by novices without any empirical verification (di Sessa 1986, Bonar & Liffick 1990). Nardi (1993) on the other hand, has strongly criticised the notion of any programming language being suitable for novices or “end-users”.

The experiments reported here have used participants without programming experience partly in order to separate the issue of notational expertise from the effect of metaphor in learning to use a notation. They also compare experts and novices. Experienced programmers have knowledge about programming that is independent of the representation being used as noted by Mayer (1988), and they apply consistent strategies for code comprehension even when using a language that does not explicitly reveal their preferred structures (Boehm-Davis, Fox & Philips 1996). The design of these experiments is based on the premise that expert programmers will out-perform novices, even using a notation they

have not seen before, and that the degree of this performance difference will provide a reference scale for the degree by which metaphor improves the performance of novices in the same task.

Experiment 1: Programming with an implicit pictorial metaphor

Despite surface similarities, the process of learning a programming language has little in common with learning a natural language. Inappropriate generalisations from natural language are a major source of confusion to programming novices. Bonar and Soloway (1985) report that novice bugs found in think-aloud protocols often result from generalisations of natural language, while Scapin (1981) found that novices make more errors when using a text editing command set derived from natural language than when using more "computational" terminology. The use of metaphor in a computer language is also unlike the use of metaphor to extend the expressive potential of natural languages (Gentner & Clement 1988). Natural language tropes such as metaphor rely on the potential for ambiguity in language (Empson 1984), while computer languages are designed to be unambiguous (Green 1980, Cohen 1993). Gentner, Falkenhainer & Skorstad (1988), in describing their structural model of metaphor interpretation, warn explicitly that the interpretation of user interface "metaphors" involves a different process to the interpretation of linguistic metaphors.

In what sense, then, can programming languages be metaphorical? The metaphor that is addressed in this experiment is an explanatory metaphor by which those learning to use the programming language understand its operation. Users of any device form a mental model of its behaviour, explaining why it responds as it does to their actions. This is true of complex machinery (Moray 1990), pocket calculators (Young 1981, 1983), computer operating systems (Tauber 1987) and automatic teller machines (Payne 1991). The mental model is sufficiently detailed to explain the observed behaviour, but does not describe all the details of the device's design (du Boulay, O'Shea & Monk 1981).

In computer science terminology, the model that defines the behaviour of a programming language is a "virtual machine". Cognitive ergonomics (van der Veer 1990) and program understanding (Tenenberg 1996) depend on whether the user's mental model is consistent with the virtual machine. Programming languages for use by novices have therefore attempted to make the virtual machine more explicit (e.g. Esteban, Chatty & Palanque 1995) perhaps most originally in the form of cartoon characters acting in a computational town of function houses and message-carrying birds (Kahn 1996). If novice programmers are not

explicitly given a virtual machine, they create their own metaphors to explain the behaviour of the language (Jones 1984). Even in languages which supposedly describe computation in purely mathematical terms, novices want to know how functions will be evaluated (Segal & Schuman 1992). If novices are not given a model of a virtual machine, they may invent an inappropriate explanation (Booth 1992, Eisenberg, Resnick & Turbak 1987, Eisenstadt, Breuker & Evertsz 1984), working from sources of information such as observing a debugger (Cañas, Bajo & Gonsalvo 1994) extrapolating from tutorial code examples (Noble 1992), or imagining the behaviour of the machine from the viewpoint of an internal agent (Watt 1998).

Programming languages must therefore serve a dual purpose: a notation for solving a problem in some problem domain, as well as representation of some virtual machine (Taylor 1990, Blackwell 1996a). Their effectiveness depends on how well information can be mapped from the problem domain to the notation, and from the notation to the virtual machine (Payne, Squibb & Howes 1990, Norman 1991). The structure of the virtual machine, and the nature of the mapping, combine to form what is often called the "programming paradigm" – families of languages that support the same programming techniques. Overly complex mappings can easily compromise performance (Nardi & Zarmer 1993), but one of the main challenges in improving programming language usability is providing metaphors that are appropriate for the user (Carroll & Olson 1988, Pane & Myers 1996, Pane 1997). Visual programming languages can potentially achieve this goal by depicting the virtual machine as if it were a physical machine (Glinert 1990) which can be understood by analogy from the user's experience of real world machines (Tauber 1987, Treglown 1994).

Metaphors of the virtual machine have been used for some time when teaching programming as well as other aspects of computer use: the effectiveness of metaphor has been demonstrated experimentally when learning programming languages (Mayer 1975), command languages (Payne 1988) and system behaviour (van der Veer 1990). Chee (1993) has proposed a theory of analogical mapping from metaphor to programming language. When the metaphor is incorporated into the language as a pictorial diagram, however, it is constantly available for inspection, unlike the situations in which mental models and virtual machines are conjectural cognitive structures. For a visual programming language, the programming paradigm and the user interface metaphor should ideally become indistinguishable.

The way that this type of metaphor is interpreted may involve very different cognitive processes from those used in interpreting textual programming languages. Diagrammatic representations of physical machines are often interpreted via a process of *mental animation.* Hegarty (1992) used this term to describe experiments in which the gaze of subjects reasoning about the motion of pulleys in a mechanical diagram followed the imagined direction of motion. Similar results have been reported by Fallside and Just (1994),

Narayanan, Suwa and Motoda (1995) and Sims and Hegarty (1997). Schwartz has shown that making a visual representation of a mechanism more or less pictorial can influence the choice of a mental animation strategy (Schwartz 1995, Schwartz & Black 1996a). In his experiments, subjects asked to assess lengths on either side of a hinged joint appeared to mentally rotate the joint into place if it was presented pictorially, but used an analytic strategy (with reaction time consequently independent of joint angle) when the pictorial detail was removed.

In the experiment presented here, two forms of a visual programming notation are used. Both express a virtual machine, and both express it diagrammatically. One of them, however, depicts the virtual machine as a metaphorical physical machine, as recommended in many of the publications cited above for teaching programming or assisting novice programmers. It uses cartoon-like representations of physical machines, intended to produce mental models corresponding closely to the virtual machine. It is also intended to encourage reasoning about program behaviour using mental animation strategies of the kind described by Schwartz (1995) and Hegarty (1992).

Notation

The diagrammatic notation used in this experiment was based on the most common paradigm for visual programming languages. In a "data flow" language, computational operations are represented by nodes in a graph. The arcs between these nodes indicate potential transfer of data between different operations. The overall behaviour of the program is defined by the topology of the graph. Data flow languages are considered to be particularly appropriate for describing concurrent computation (Finkel 1996), but the claim that they provide advantages to any particular class of user by assisting comprehension, problem-solving or program design is still under investigation (Karsai 1995, Good 1996).

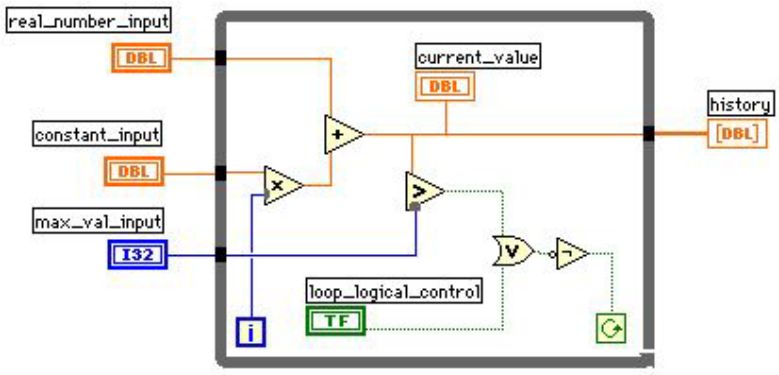


Figure 4.1. Example of LabVIEW program

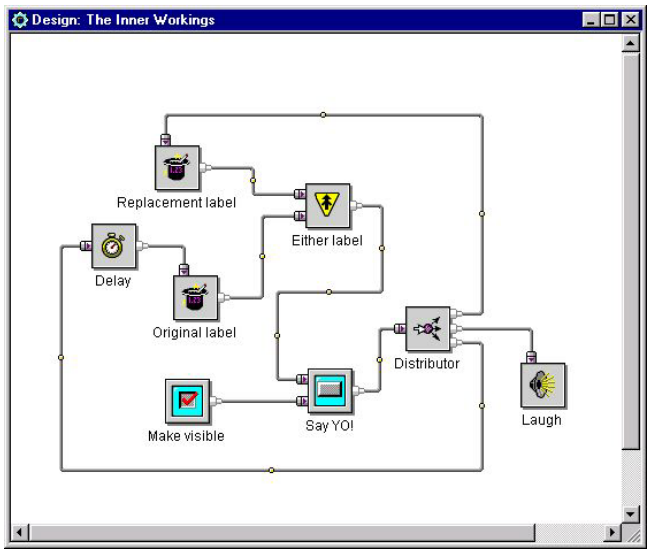
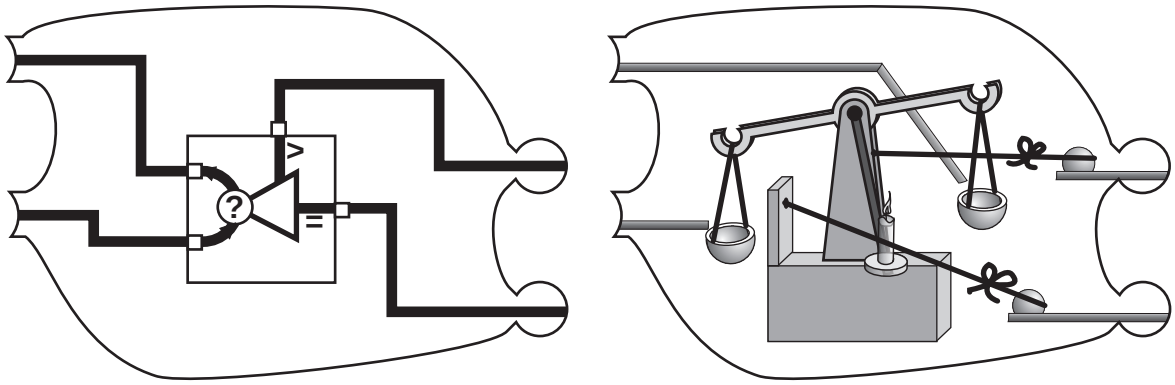


Figure 4.2. Example of JavaStudio program

Dataflow is already considered particularly appropriate for exploitation in commercial visual programming languages, however. Two examples of commercially available visual programming languages employing dataflow are illustrated in figures 4.1 and 4.2. Both describe dataflow in a metaphorical way, although the metaphors are presented using different modes. The LabVIEW language, shown in figure 4.1, depicts the paths between nodes as simple lines (although these are coloured to indicate the type of data). The documentation for LabVIEW, however, describes these lines metaphorically as "wires" like those connecting components in an electronic circuit. The JavaStudio language, shown in figure 4.2, depicts paths as miniature pipes, including visible plumbing joints. The metaphor implicit here is that data flows from one component to another like a fluid through plumbing.



a) without metaphor **b) with metaphor**

Figure 4.3. Comparison operations without and with metaphor

Two different presentation modes were also used in this experiment. In one of them, nodes were connected together using unadorned lines, and the nodes themselves were represented as abstract symbols. An example of one of these nodes, representing a comparison operation, is shown in figure 4.3a. The symbol provides some mnemonic assistance using mathematical conventions, but there is no explicit physical metaphor. In the second presentation mode, nodes were connected by tracks with balls rolling along them. The nodes themselves were fanciful "Heath Robinson" mechanisms showing a computational function implemented by controlling the motion of balls, as in the proposed ball-bearing computer described by Pilton (1971). A comparison operation, in which an arriving ball is weighed against a predefined value to determine the outcome, is shown in figure 4.3b.

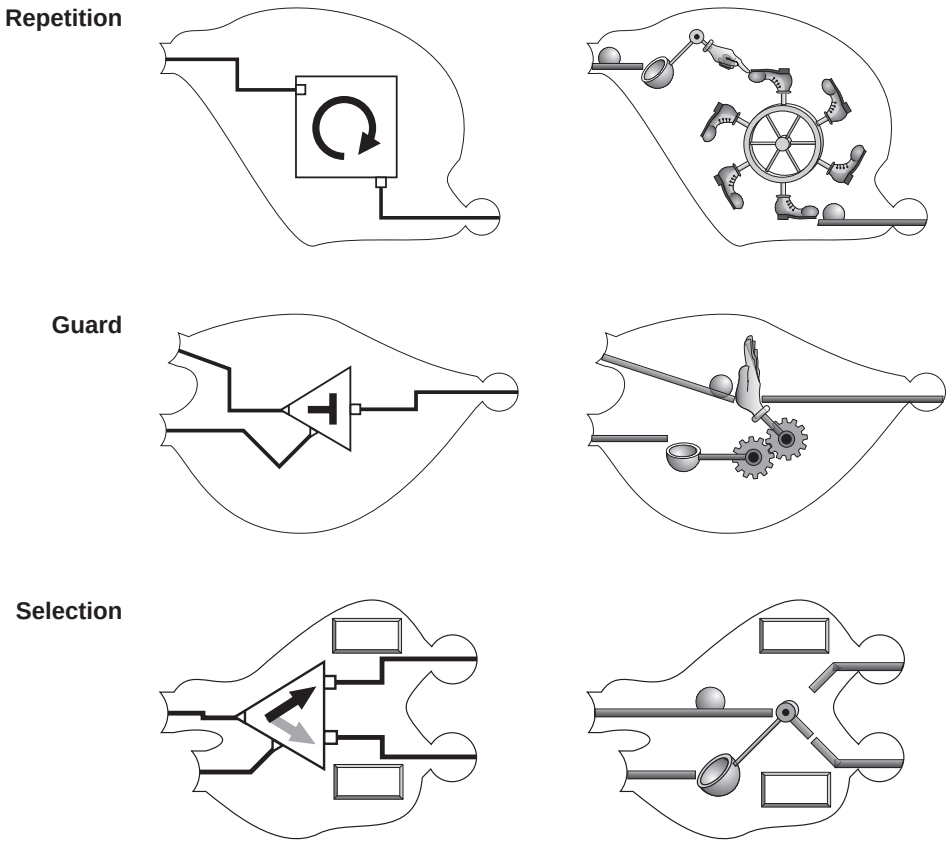


Figure 4.4. Examples of computational operations

These two versions of the dataflow notation, one depicting dataflow metaphorically as the motion of balls, and the other using a relatively simple geometric depiction, were otherwise made as similar as possible. The component nodes and connections between them were given to participants in the form of paper cut-outs, whose profiles were identical in each version. Figure 4.4 shows a selection of computational operations, comparing the two versions of each (the full set of components is reproduced in Appendix B.1). Participants arranged these cut-outs on a tabletop by matching the convex data outputs on the right hand side of node and path profiles to the concave data inputs on the left hand side of another node or path. Figure 4.5 shows an example of a complete program (using the metaphorical notation) which would simply display the numbers from 1 to 10.

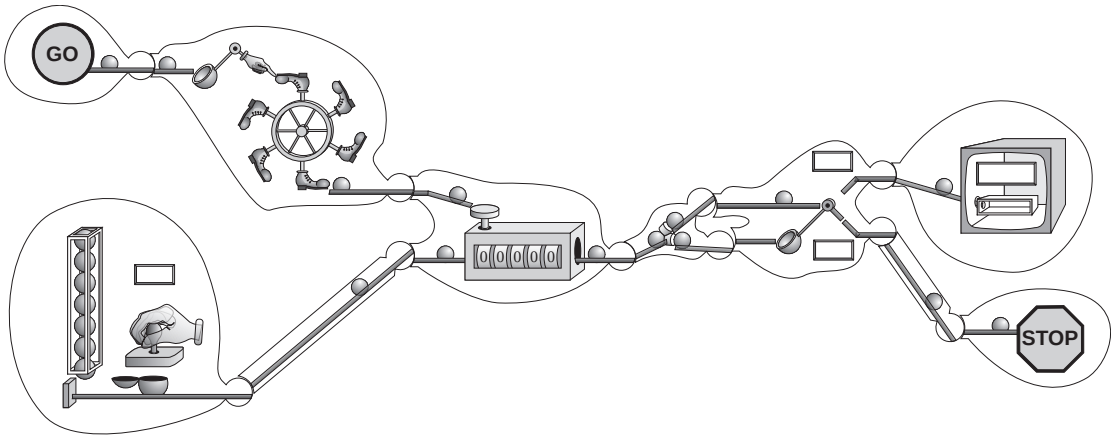


Figure 4.5. Example program: display numbers from 1 to 10

Tasks

The task domain used in this experiment was intended to be equally familiar to programmers and non-programmers. Following the advice of Lave (1988), I designed four tasks based on a regular household task – the inspection of bank statements. Participants were asked to interpret or write programs that would carry out the following functions:

- add total credits and debits on a statement;
- find missing cheque numbers in the sequence of those included on the statement;
- print out the locations in which cash withdrawals had been made; and
- automatically write cheques for the same amount as in the previous month.

A transcript of the instructions and task specifications is included in Appendix B.1.

Equipment

Although the tasks were performed using paper cut-outs rather than a computer editing environment, the table top was arranged in a way that resembled typical visual programming languages. Figure 4.6 shows trays at the right hand side of the table, made to resemble a software "palette". The trays were divided into compartments, each containing a pile of one type of component.

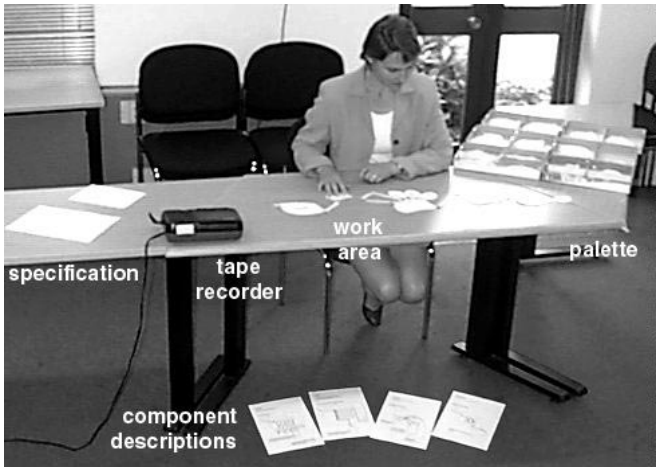


Figure 4.6. Experiment 1 working environment

The behaviour of each component was described on individual printed pages. When using a component for the first time, participants were given one of these descriptions to read, but it was then placed out of view of the participant, who could ask to see it again at any time. This was intended to be similar to the operation of an on-line help facility.

Participants were also given a mock-up of a bank statement to be used for reference during the bank statement processing tasks.

Hypotheses

1. That the provision of a diagrammatic metaphor will make it easier for novices to learn to write computer programs.

2. That this assistance will reduce the differences in performance that would normally be expected between novices and expert programmers.

3. That novices will think in terms of the metaphor when reasoning about the computational virtual machine.

Participants and design

Twelve participants were recruited from volunteers registered with the Applied Psychology Unit Subject Panel, and from amongst staff at the Unit. They were divided into two groups on the basis of their prior experience of computer programming. Four participants had previously worked as professional *programmers*; eight had never written a computer program

("*novices*"). The second group were broadly matched in educational achievement and intelligence to the experienced programmers (they were educated to degree level, and during previous experiments at the APU, their scores on Cattell's Culture Fair test had corresponded to an IQ of between 120 and 140).

The second independent variable was the version of the data flow notation given to the participant, either with or without the rolling ball metaphor. Assignment was balanced within each experience group: I presented each version of the notation to four non-programmers, and to two of the programmers. I made this allocation in the expectation that the metaphor would bring novice performance closer to that of the expert programmers, whereas it would have little effect on the experts. If this were the case, the expert programmers could be aggregated into a single group for analysis, and the performance of this group would provide a point of reference for the claim that metaphor can improve the performance of novices with respect to experts.

Performance was measured using two dependent variables. The first was the total *time* that the participant took to complete each of the four activities described below. The second was the degree of *elaboration* that the participant produced in the two program construction tasks. The program specification that they were given allowed several different solutions, but complete solutions had similar degrees of complexity, while incomplete solutions omitted some of the required components. The relative quality of the solutions might be subject to interpretation, but the degree of completeness could be estimated by the simple measure of the number of nodes included. The third dependent variable was the number of times that participants asked to *review* component explanations after they had initially read them.

Three further dependent variables were used to measure awareness of the metaphor. A think-aloud protocol was recorded while the participant worked on each task. I compared the vocabulary of these protocols in order to identify the frequency with which the participant referred to the problem domain, to the computational metaphor, and to abstract mathematical or computational terms. These were compared using three different vocabulary classifications: *nouns* were classified according to the domain they referred to, *verbs* were divided into physical and abstract behaviour, and descriptions of *flow* were classified into references to the virtual machine and references to the problem domain.

The first two hypotheses were assessed on the basis of the time and elaboration performance measures, comparing performance of novices to that of experts, and also comparing performance with and without diagrammatic metaphor. The effect of the metaphor on learning was evaluated in terms of the number of review requests made by participants.

Vocabulary in the think-aloud protocols was used to evaluate the extent to which participants used the metaphor when reasoning about the program.

Procedure

Before the start of the experiment, I instructed participants in the procedure for "thinking aloud" during problem solving, using the instructional procedure prescribed by Ericsson and Simon (1993). As the participant performed each task, the tape recorder seen in Figure 4.6 recorded this verbal protocol. In order to confirm the assumption of task domain familiarity, I asked all participants to confirm that they were familiar with bank statements.

For the first task, I demonstrated the creation of a program to add total credits and debits, describing the operation of the program as each component was added. I read the description from a script that was identical in the two versions of the language (this script is included in appendix B.1). The participant was shown a description of each component as it was added to the program, which they read at their own pace. The layout of the component descriptions is shown in figure 4.7. Only the picture was changed in the two versions of the language – the description texts were identical (the full set of component descriptions is reproduced in Appendix B.1). After the program was complete, I shuffled the paper components, and asked the participant to reassemble to program while thinking aloud.

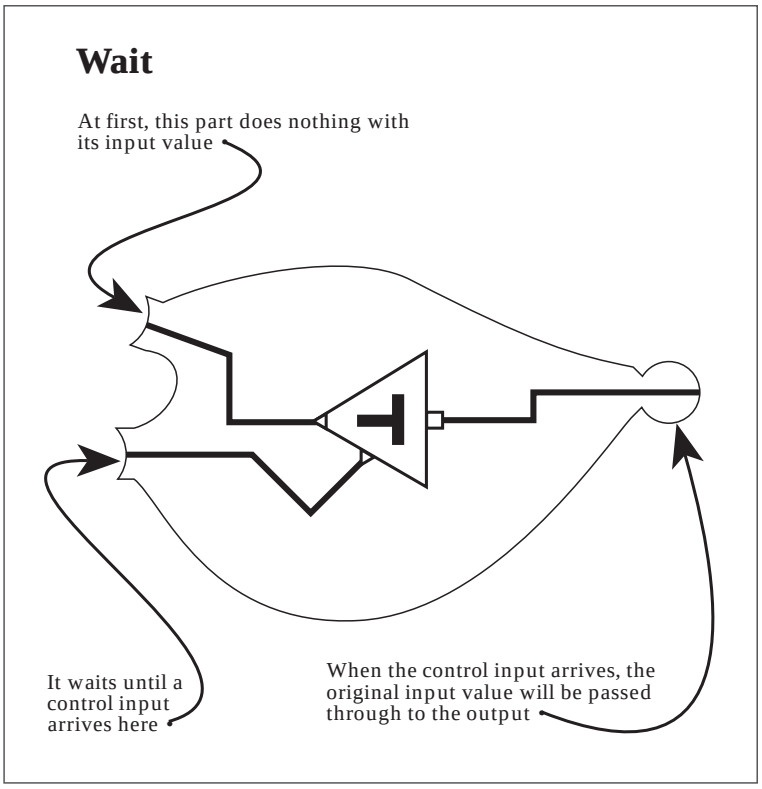


Figure 4.7. Layout of component descriptions

In the second task, I showed a completed program to the participant, printed to the same scale as the paper cut-outs on the tabletop. I told the participant that the program was designed to find missing cheque numbers in a sequence, and asked them to explain how it worked. The program contained an error (it compared each number to itself rather than to the previous one in the sequence), and I asked them to find this error and suggest a way of fixing it. This program included two more components that had not been used in the first task, and I described the function of these components in the same way as before.

In the third task, the participant was given a description of a program that would check the locations of cash withdrawals, and display any that had been made outside Cambridge. I then asked the participant to create a program that would carry out this function. As before, I described a further component that would be required in this task.

In the final task, the participant was given a description of a program that would find a cheque paid to a particular recipient, and automatically write another cheque for the same amount. I did not describe any new components, but told the participant that some new components would be required. When this occurred, they were to use “mystery components”

that could be defined to carry out new operations, as when designing an encapsulated function in a real programming language.

Throughout the experiment, each component was described only once. Participants read at their own pace, but the description page was then placed beyond reading distance. They were able to review the description of any component by asking to see the page again, as in an online help facility.

Results

The experimental hypotheses express the expected improvement in performance resulting from use of metaphor in terms of time taken to complete all the tasks, and elaboration in construction tasks. The effect of metaphor on these measures is considered with respect to the differences between novices and experts.

The four expert participants are considered as a single group in this analysis. I did not expect to find a large effect of metaphor on expert performance, and the experiment was intended to assess its utility for novices. Two of the four experts used the metaphorical version of the notation, and two used the geometric version. The performance measures for these groups were, as expected, similar – they are summarised in table 4.1. No significant differences were observed, but the size of the groups is too small to draw any further conclusions regarding the assumption of homogeneity.

Performance measure	With metaphor	No metaphor
Time to complete four tasks (h:mm:ss)	0:28:27	0:41:50
Elaboration in construction tasks	23.5	23.0
Number of review requests	5.0	6.5

Table 4.1. Performance measures within expert groups (N=2)

There were significant differences between the two novice groups and the expert group in the levels of performance observed. Novices took an average of 57 minutes to complete the four tasks, while the overall average in the expert group was 35 minutes, $F(1,10)=6.07$, $p<.05$. Experts also produced solutions that were more elaborate: 23.25 components on average, versus 18.13 for novices, $F(1,10)=19.66$, $p<.01$. The difference between the number of review requests made by novices and experts was not significant, for reasons discussed below.

Performance measure	With metaphor	No metaphor
Time to complete four tasks (h:mm:ss)	0:53:42	1:00:19
Elaboration in construction tasks	17.8	18.5
Number of review requests	7.0	17.0

Table 4.2. Performance measures within novice groups (N=4)

The main hypothesis in this experiment was that the novice group given the metaphorical version of the language would be intermediate in performance between novices with no metaphor and experts. The relative performance of the three groups is compared in figure 4.8. Although there is a significant difference between the expert and novice groups in task completion time, there is no significant difference between the two novice groups, $F(1,6)=0.33$, $p=.586$. The same is true of the elaboration measure, $F(1,6)=0.57$, $p=.477$.

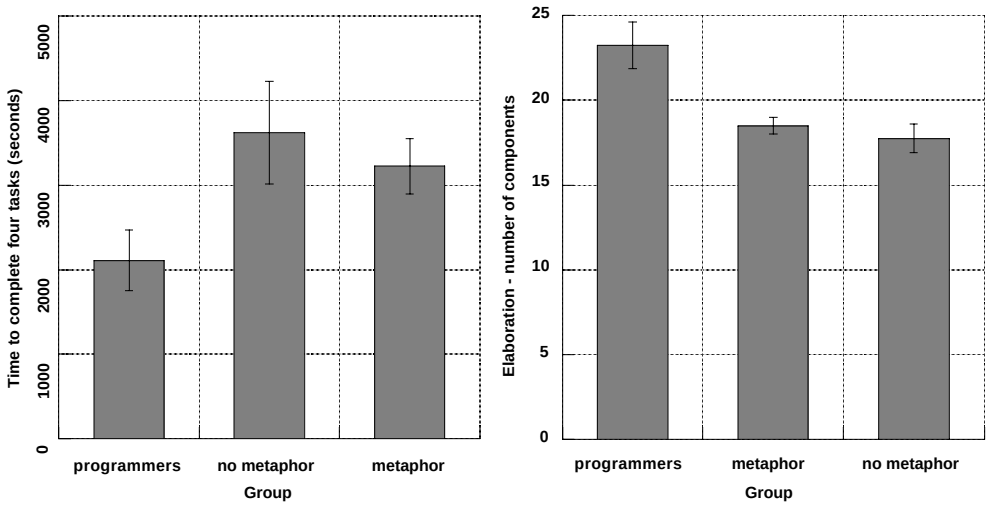


Figure 4.8. Comparison of expert performance to novices with metaphor

The first hypothesis referred specifically to the effects of metaphor on learning, rather than on performance. There is an effect in the expected direction on the mean number of times that novices asked to review the component explanation (see table 4.2); the mean number of requests is much higher in the novice group with no metaphor. This difference is not statistically significant, however, $F(1,6)=3.35$, $p=0.117$. The large difference is in fact due to only two of the four participants in the no metaphor condition – the other two made review requests no more often than those in the metaphor condition. The effect of metaphor on learning is investigated with a larger sample of novice programmers in the next experiment,

and in the experiments discussed in chapter 6, where it is found to be a significant source of variation.

In order to measure the extent to which the dataflow metaphor was used in reasoning about the notation, I compared the vocabulary used by novices in the verbal protocols. This involved three separate comparisons. The first two were comparisons of the categories of noun phrases and verbs found in the protocol transcripts. Noun phrases were divided into references to the virtual machine, references to the metaphor, references to the problem domain of bank statements and references to other material (material outside the scope of the experiment). Figure 4.9 shows the mean number of references made in each category by the three experimental groups. The most significant observation is that none of the participants in the metaphor group ever referred to the implicit metaphor while thinking aloud. Neither are there any other significant differences between novices in the metaphor and no-metaphor group. Experts do, however, make significantly more references than novices to the problem domain while thinking aloud, $F(1,10)=12.12$, $p<.01$.

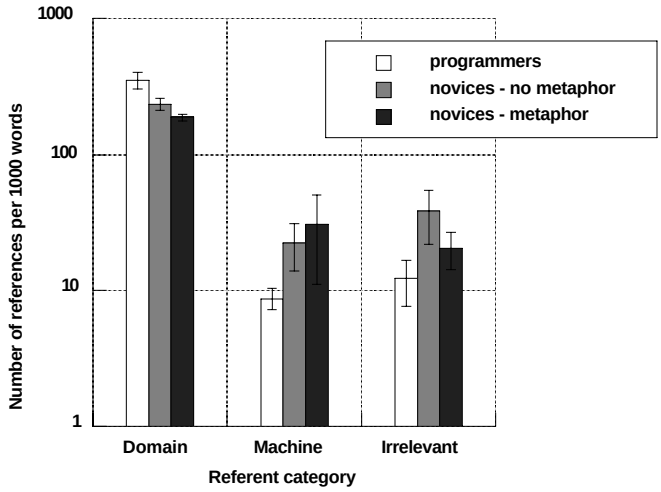


Figure 4.9. Distribution of transcript noun phrase referents

In a second analysis of vocabulary, all verbs in the protocol transcripts were classified into categories comprising references to motion, propulsion, decision, alteration, expression, state change, observation, layout, arithmetic, ownership, mental process, and necessity. If participants were thinking of a virtual machine in terms influenced by the metaphor, they should be more likely to use verbs of motion or propulsion.

Most participants used a rather constrained vocabulary while thinking aloud, some of them using certain verbs continually. This resulted in a skewed distribution of category sizes

between subjects, and of vocabulary within the categories. I therefore based this analysis on log transformed frequencies of verbs within each category, relative to the total number of verbs used by that participant. The log frequencies for each verb category are illustrated in figure 4.10. No significant differences were found between the metaphor and no-metaphor cases in these distributions.

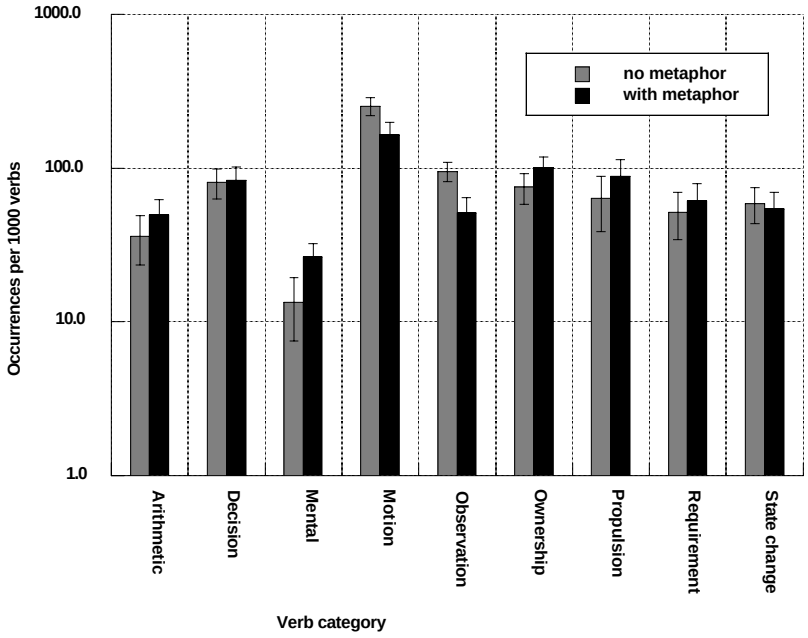


Figure 4.10. Log frequency distribution of transcript verb categories

A third comparison of the verbal protocols concentrated specifically on occasions when participants described interaction between components. These were divided according to the type of information or entities that were described as moving between components: they could refer to program values (either control information or specific data), to entities in the problem domain (such as account numbers), or to abstract entities (such as "item", "value" etc.). The number of references that fell into each of these categories is shown in figure 4.11. There are no significant differences between the first two categories in the metaphor and no-metaphor conditions, but there is a large difference in the number of references that are made to abstract values moving between components, $F(1,6)=12.07$, $p<.05$.

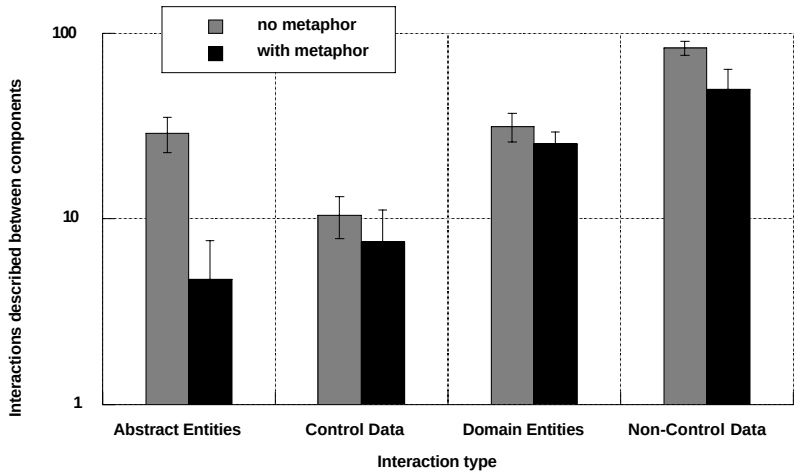


Figure 4.11. Descriptions of interaction between components

Discussion

The measures used in this experiment were successful in measuring different levels of performance – they clearly distinguished between the expert and novice groups. Despite the fact that the measures appear to be sufficiently sensitive, the expected improvement in performance when novices were given a metaphorical diagram was not observed. This is a new finding in HCI. Some previous experiments in HCI areas other than programming have failed to find improvements in performance when metaphors are introduced (e.g. Eberts & Bitianda 1993; Sutcliffe & Patel 1996), but those studies have generally suggested that specific usability problems reduced the benefits expected of an otherwise valuable interaction metaphor.

The design of this experiment did assume that expert programmer performance would be relatively consistent, whether or not they were given an explanatory metaphor. This expectation was derived from studies of expert programmers such as that of Scholtz & Wiedenbeck (1992), who observed that experts learning a new language used strategies already familiar to them, rather than learning how the features of the new language might require a different approach. A similar effect may, however, have resulted in the unexpected consistency in novice performance. Studies of novice programmers have observed that, while they cannot transfer strategic knowledge from other programming languages, they do transfer the structures of everyday tasks into the programming domain (Eisenstadt, Breuker & Evertsz 1984) and that this produces strategic preferences for procedural explanations even

where a programming language (Prolog) encourages declarative explanations (Noble 1992). This type of strategic transfer may have reduced reliance on the metaphor in this experiment.

It is possible that novices simply ignored the illustrations, as their attention was never drawn to them explicitly. This behaviour has been observed in studies of illustration by Wright, Milroy and Lickorish (in press). It may be a sensible strategy for readers whose comprehension and reading speed would otherwise be reduced by the effort involved in integrating text and illustrations, as observed by Willows (1978) in studies of reading speed in children, and by Mayer and Sims (1994) in a comparison of students with high and low scores on spatial reasoning tests. Advice on illustrating educational material also recognises that some students are likely to follow a text without attending to illustrations (Dale 1969). Furthermore, several participants in this experiment commented that they found the illustrations unsympathetic (the experts, however, found them entertaining). This element of affect may have caused novices to give less attention to the illustrations. The problem of metaphors that users simply do not like has previously been noted in HCI by Halewood & Woodward (1993), and Pinkpank and Wandke have observed anxiety when users are asked to use interfaces that they expect to be difficult (1995). These effects may inhibit use of graphical metaphors in the same way that Hesse, Kauer and Spiers (1997) have noted reductions in analogical transfer when the source domain has negative emotional connotations.

Evidence taken from the verbal protocols in this experiment does suggest that novices may not have been aware of the metaphorical illustrations. Alternatively, participants may have reasoned about the motion of the metaphorical machines using mental animation strategies that are not accessible to verbalisation, as noted by Schwartz and Black (1996a). Lowe (1993b) makes a fundamental criticism of the use of verbal protocols in diagram experiments for this reason, although other researchers have defended their use in more general studies of HCI (Fisher 1987). The critiques of Schwartz and Black or Lowe are relatively benign, however. A more worrying possibility is that verbalisation altered performance by "overshadowing" insights that might otherwise have been derived from the visual material. Early studies in problem solving considered that verbalisation improved performance by forcing participants to think (e.g. Gagné & Smith 1962, Berry 1990), but Schooler working with several colleagues has found that verbalisation impairs performance on non-verbal memory tasks (Schooler, Ohlsson & Brooks 1993, Brandimonte, Schooler & Gabbino 1997, Melcher & Schooler 1996).

The requirement of verbalisation may also have imposed an unnecessarily linear structure on the way that participants used the visual representation. The imposition of narrative structures on visual and spatial material is well documented in experiments involving description of geometric structures (Levelt 1981) and of building layouts (Linde & Labov 1975) although

Taylor and Tversky (1996) noted that the study by Linde and Labov may simply have reflected linear structures in their experimental task. Davies and Castell (1992) have also noted that expert programmers tend to rationalise their problem solving processes to comply with recommended design methods when thinking aloud during programming tasks. In recognition of these concerns, think-aloud protocols were not used in any of the other experiments described in this thesis.

Notwithstanding any possible effect of verbalisation on reasoning strategy, the visual metaphor used in this experiment may have improved mnemonic performance as a result of dual coding effects (Paivio 1971, 1983), Two of the four novices working without an explanatory metaphor made many more requests to review the diagram component definitions. This may indicate that lack of a metaphor made the definitions more difficult to remember, but it is not possible to draw definite conclusions when the effect was only observed among half of a small treatment group. The potential effect of explanatory metaphors on memory for diagram definitions is examined in far more detail in chapter 6. No similar effect was observed in experts, but this is unsurprising. Firstly, the computational domain provides a familiar context within which experts could encode the definitions of the components. Secondly, studies of experts in other domains have shown that they are more likely to attend to configuration in abstract material while novices attend to surface detail (Hekkert & van Wieringen 1996, Lowe 1993b).

The interaction between representational detail and abstraction is perhaps the most interesting observation to be drawn from the verbal protocol data in this experiment. It appears that novices may have inhibited abstract descriptions of the problem when using the metaphorical representation. Several observers have noted that the use of concrete representations can limit the formation of abstractions in fields such as mathematics education (Pimm 1995), learning programming (di Sessa 1986) and more general educational contexts (Dale 1969). This may lend support to theories describing the limitations of visual representations for reasoning about abstraction (Wang, Lee & Zeevat 1995, Green & Blackwell 1996b) or negation Dopkins (1996). A more prosaic potential explanation is that the version of the notation with geometric symbols, having a cultural association with technical matters, may have encouraged participants to use “technical” terms that would not otherwise be common in their vocabulary. Similar instances of novices adopting an overtly technical vocabulary have been observed before by van der Veer, van Beek & Cruts (1987) and Scapin (1981). The apparent relationship between geometric notations and abstract reasoning is investigated in far more detail in chapter 5.

Experiment 2: Comparison of systematic and nonsense metaphors

Experiment 1 failed to find the anticipated benefits of incorporating a metaphorical virtual machine in the design of a visual programming language. Those benefits were expected on the basis of much previous research describing mental models and virtual machines in programming. Experiment 1 could be refined and extended, further to investigate the cognitive tasks involved in programming, such as those reviewed by Davies (1993). The main concern of this thesis, however, is to explore the claims that visual representations support abstract problem solving through their metaphorical reference to entities and structures in the physical world. The validity of those claims is widely assumed in visual programming language research, as described in the surveys of chapter 3. The results of this investigation can therefore be relevant to visual programming language design, without covering the same ground considered in many other theories of program construction.

This second experiment therefore considers experimental tasks that do not, on the surface, resemble computer programming. Neither were participants told that the experiment had any relationship to computer programming. Instead, it attempts to isolate the use of metaphor to represent abstract concepts in physical terms. In this experiment, moreover, the diagrams do not resemble physical machines. The metaphorical interpretation is provided in explanatory text, in a way that is more typical of visual programming languages, where the diagrams are displayed using simple geometric elements, and users are only aware of the metaphor as a result of explicit instruction.

Notation

The four diagrams used in this experiment did not refer specifically to computer programs, although they expressed concepts that are more often found in computer programs than in everyday life. I presented the diagrams to participants using (slightly contrived) non-software task contexts where the concepts could be applied. The four computational concepts were:

- closure (a set of values that is defined for use in a specific context);
- database join (combining tables of data on the basis of common values in each table);
- flow of control (sequences of execution states such as repetition and choice); and
- visibility (hiding working material within a function to simplify its interface).

I developed four diagrams to express these concepts, based on verbal descriptions of the concept by Finkel (1996), and employing conventional symbolic elements from fields other than software, as collected in Dreyfuss (1972). The explanation of each diagram incorporated either a *systematic* metaphor that compared the graphical elements to some physical situation

with an appropriate structure, or a *nonsense* metaphor that compared them to an irrelevant physical situation.

The diagram expressing closure is shown in Figure 4.12. The task context described a sports team on tour, where a playing side is allocated for each game. The diagram shows each game as a separate line, with the original tour team at the bottom of the diagram, and successive games drawn above that line. The introduction of new players is shown as a "bump" in the appropriate position corresponding to the player in the original team who has been replaced.

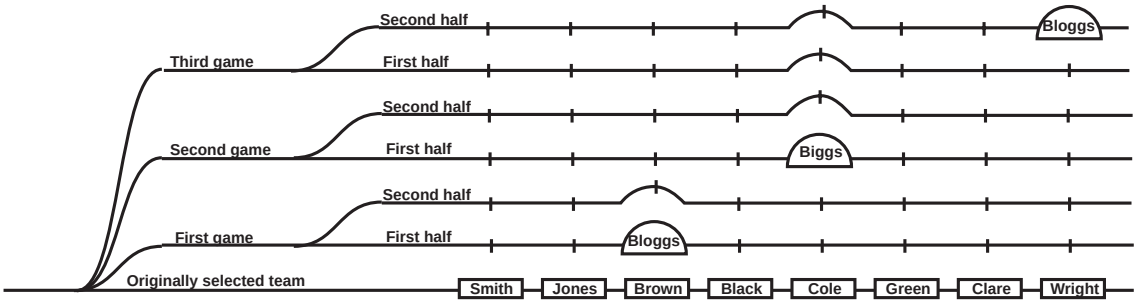


Figure 4.12. Diagram showing closure in terms of sports teams.
Eg: Cole plays in the first game, but is replaced by Biggs for the second and third

For this diagram, the systematic metaphor described the lines as layers of new surfacing laid on top of a road, so that the inclusion of new material is visible as a bump in later layers. The nonsense metaphor described the overall shape as an ice-cream cone with jelly beans stuck in it, and the junction at the left of the diagram as a fork.

The diagram expressing database joins is shown in Figure 4.13. The task context described an airline booking system, in which a flight information table must be matched with a passenger booking table and a checked luggage table. Each table of information is shown as a vertical line of connected data items. Where tables are joined on particular data items, those items are linked together by a line drawn between the appropriate items. The data items that will be returned as the result of the join are indicated by a funnel shape at the side of each selected item.

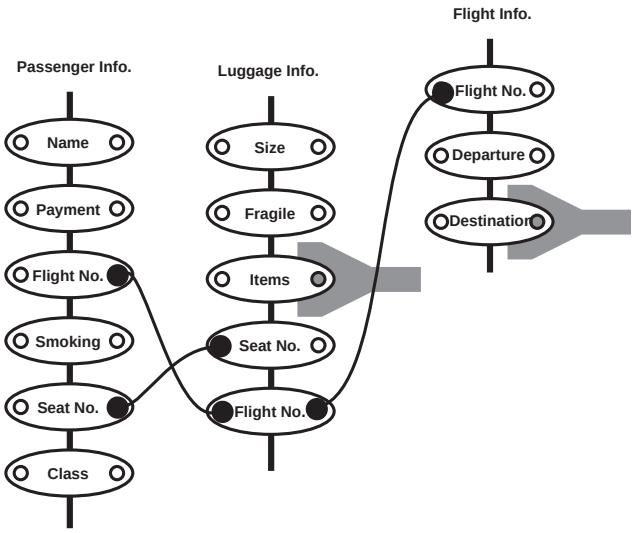


Figure 4.13. Diagram showing database join in terms of airline bookings.
Eg: find all records of passengers and luggage on a particular flight, and match them by seat number

For this diagram, the systematic metaphor described the vertical lines as tags threaded onto pieces of string, with matching tags joining the pieces of string together. Output of data items was described in terms of the tags dropping into funnels. The nonsense metaphor described the lines as cracks in a flagstone, and the circles as manhole covers which were dangerous when missing.

The diagram expressing flow of control is shown in Figure 4.14. The task context described a washing machine cycle, in which a range of processes must be started, stopped or repeated a certain number of times according to conditions such as water level and temperature. Each process is shown as a circle, which may include other sub-processes. The signal to start a process is shown by a line with a star at the end, while a stop signal is shown by an arc at the end. One process can be made to start when another stops, shown by a jagged line at the first process.

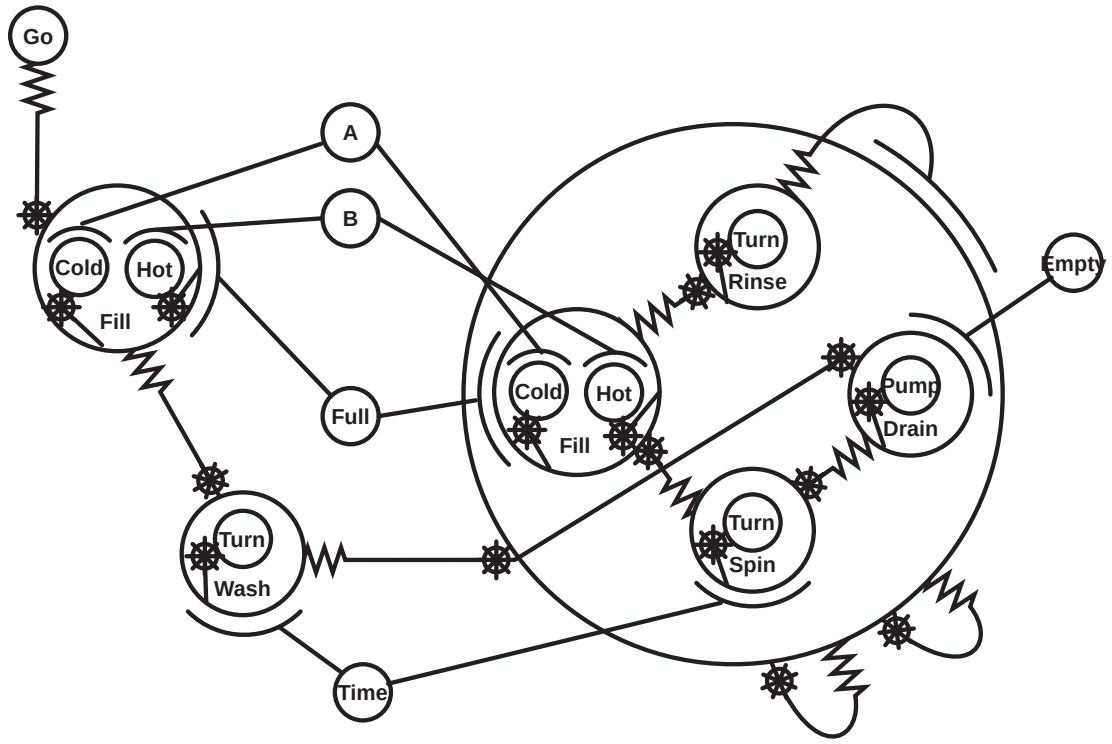


Figure 4.14. Diagram showing flow of control in terms of a washing machine cycle.
Eg: Once filling has completed, start washing, until a fixed time has elapsed

For this diagram, the systematic metaphor described the process circles as turning cogs. The star showing when a process starts resembles a starting cog, while the arc showing when it stops resembles a brake shoe. The jagged line is a spring which rebounds when the cog that it is attached to stops. The nonsense metaphor described the circles as rock pools, with the stars and jagged lines resembling starfish and worms. As in experiment 1, the dynamic nature of the systematic metaphor in this case was intended to support depictive mental animation as proposed by Schwartz and Black (1996a, 1996b), whose experimental investigation of reasoning from mechanical diagrams did in fact describe a diagram based on turning cogs.

The diagram expressing visibility is shown in Figure 4.15. The task context described a telephone switchboard in a large organisation. There are some people in the organisation who would never deal directly with queries from the public, while others would often do so. This diagram is a modification of an organisation chart, showing which people are prepared to deal with the public (a circle by their name, rather than a square or half-circle), and how calls might be referred by the receptionist from one person to another (dashed lines).

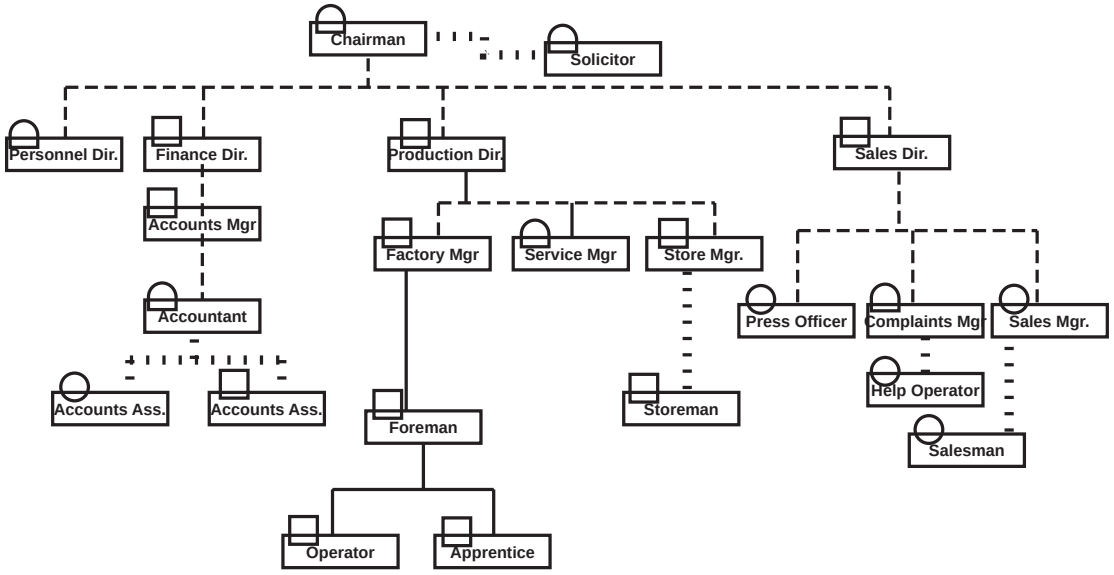


Figure 4.15. Diagram showing visibility in terms of a telephone switchboard.
Eg: one of the accounts assistants will always take queries from the public, while the other never will

For this diagram, the systematic metaphor described the chart as a railway network, and each person's office as a station. The circle represented a public revolving door, the square a closed door, and the half circle a door that was ajar. The different dashed lines represented the relative priority of railway lines and roads. The nonsense metaphor described the diagram as representing an airport, with circles being bicycles, the squares garages, and the half circles as aircraft hangars. The dashed lines were described as rows of people sitting behind each other on an aircraft.

Tasks

After reading the explanations of the diagrams, participants completed three different tasks using each diagram. In the first task, participants answered comprehension questions relating to an example of the diagram. These questions were phrased to involve an element of

problem solving using the notation, rather than simply providing definitions of diagram elements, or reading information directly from the diagram.

In the second task, participants completed an incomplete diagram. The diagram was accompanied by text stating, in terms of the problem domain, what information was missing. Participants then completed the diagram by drawing the missing graphical elements in appropriate places. An example constraint for the closure diagram is: "Bloggs played in the whole of the first game, and also in the second half of the third game. Biggs was substituted for the whole series after Cole was injured." (This is the constraint shown in figure 4.12).

The third task also involved completion of an incomplete diagram. In this task, participants completed the diagram by writing missing labels onto a diagram that was otherwise complete. As before, the position of the labels was deduced from text describing a problem situation, and listing the labels that were to be added. An example for the visibility diagram is: "The *service manager* can be contacted sometimes, but does not pass on queries, the *store manager* would always pass on queries to the *storeman*. The *production director* can only receive queries from the *chairman*."

All task instructions, together with the diagram they apply to, are reproduced in Appendix B.2.

Equipment

The experimental material was presented as a bound booklet containing both explanations of the diagrams and comprehension tests. Participants were instructed to work through the booklet in order, without turning back to look at previous pages. At the top of each page was a box where the participant wrote the time when they started work on that page. Participants read the time from a large stopwatch placed on the table in front of them.

Hypotheses

1. That experts would perform better than novices.

2. That metaphor would bring novice performance closer to expert.

3. That metaphor would have little effect on experts.

Participants and design

Sixteen participants were recruited from two different populations. The first independent variable was level of expertise in these populations: eight participants were volunteers registered with the APU Subject Panel, none of whom had any experience of computer programming ("*novices*"). The other eight were experienced *programmers* employed at the Advanced Software Centre of Hitachi Europe Limited. A further two programmers were recruited from the same population after two of the expert cohort did not complete the experiment. This was as a result of work-related interruptions. The two who were replaced are not considered any further.

The second independent variable was the type of metaphor provided in the explanation of the diagram. This was varied as a repeated measure: each participant received two explanations with the *systematic* metaphor, and two with the *nonsense*. Diagrams could not be presented to a given participant with both forms of the explanation, however. This design was therefore a balanced confound between diagram and metaphor type.

The order of the four diagrams was balanced within each group of eight participants. The order of the instruction types was not varied; a pilot experiment had shown that if participants received the nonsense metaphor first they would ignore the rest of the metaphors as being irrelevant. Presentation order was therefore: systematic, nonsense, systematic, nonsense.

The third independent variable was the type of task performed: answering *comprehension* questions, *drawing* missing graphical elements on an incomplete diagram, and *writing* missing text on an incomplete diagram. The three types of task were always presented in this order.

There were two dependent variables. The first was the *speed* with which participants completed each comprehension task. The second was *accuracy* on the comprehension tasks. The possible total score for each diagram type and comprehension task varied according to diagram complexity, but the balanced confound design meant that it was necessary to compare scores between different diagrams. I therefore calculated a normalised score for each task, in which the lowest score was assigned a normalised value of zero, and the highest a value of 100. All other scores were normalised by a linear interpolation between these values.

The three hypotheses are described in terms of relative performance, which was evaluated in terms of both speed and accuracy in order to identify possible speed-accuracy trade-offs made by participants.

Procedure

Participants read a page of general instructions at the front of the booklet, then worked through at their own pace, writing the time at the top of each page as instructed. (The instructions are reproduced in appendix B.2).

The experimental procedure was determined by the order of the pages in the booklet. The order was as follows:

Page	Contents
1	General instructions: completing the booklet, and writing times.
2	Explanation of an example of the first diagram.
3	Questions testing comprehension of the first example.
4	Explanation of an example of the second diagram.
5	Questions testing comprehension of the second example.
6	Explanation of an example of the third diagram.
7	Questions testing comprehension of the third example.
8	Explanation of an example of the fourth diagram.
9	Questions testing comprehension of the fourth example.
10–13	Drawing missing elements on examples of each diagram.
14–17	Writing missing text on examples of each diagram.

Table 4.3. Booklet presentation order

The comprehension questions were scored by awarding one point for each item of information that corresponded to the worked solution, and subtracting one point for each incorrect piece of information. Drawing tasks were scored by awarding a mark for each element added in an appropriate place and a further mark if the element was the correct shape. A mark was subtracted for each unnecessary element, and a further mark if the additional element violated either the task constraints or the original diagram definition. The writing task was scored by awarding a mark for each label written in the correct place, and subtracting a mark for each label written in a place that violated the constraints.

Results

The first hypothesis was that experts would perform better than novices. The times taken by each group to complete the three tasks, as well as the mean accuracy achieved by each group, are shown in Figure 4.16. Analysis of variance (ANOVA) indicates that experts were significantly more accurate, $F(1,14)=5.48$, $p<.05$. Experts did not finish the tasks more quickly - in fact they spent slightly longer, but this difference was not significant.

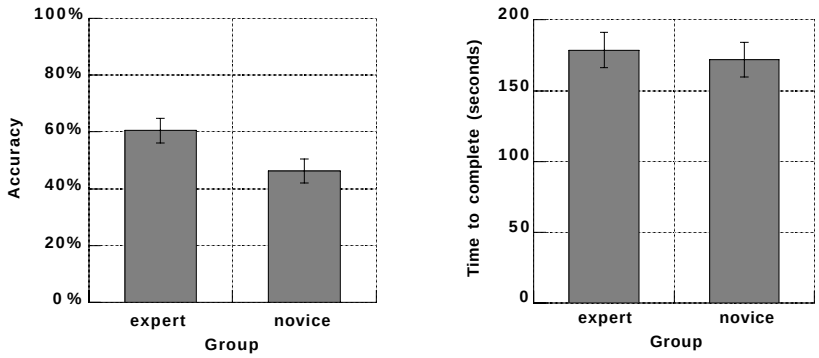


Figure 4.16. Relative performance of experts and novices

The second hypothesis was that a systematic metaphor would bring novice performance closer to that of the experts. Figure 4.17 shows the interaction between expertise and metaphor type. As expected, accuracy is poorer when the nonsense metaphor has been given. This difference does appear to be greater for novices than for experts, but the interaction is not significant. The effect of this interaction on the time taken to complete the tasks indicates that novices spend more time trying to use the nonsense metaphor, while experts spend less time. This interaction is not significant either, however.

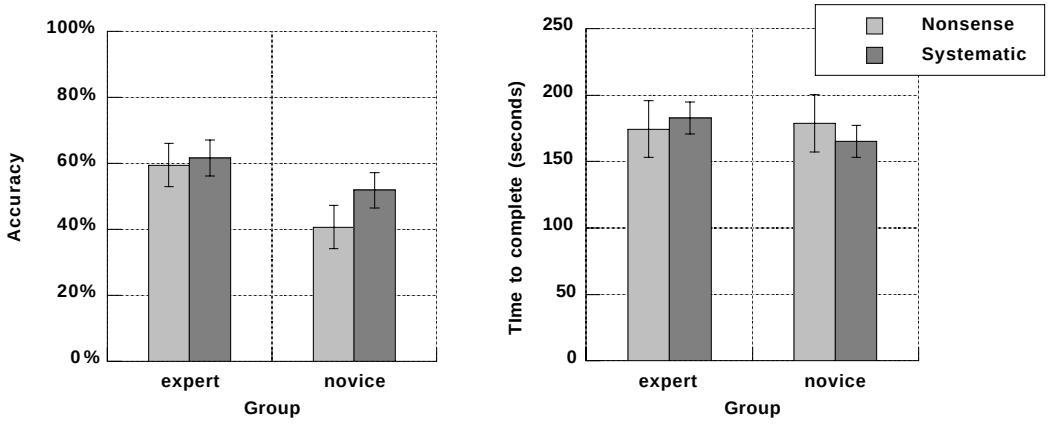


Figure 4.17. Interaction of systematic metaphor with expertise

There was a significant interaction of task type with experience, $F(2,28)=5.60$, $p<.01$. Experts performed best in the task where a diagram was completed by drawing in missing elements. Novices performed more poorly on this task than on other tasks, with an average drawing score of 34%, versus 65% for experts. If the effect of metaphor is considered separately for

each task type within the novice sample, metaphor appears to have had no effect at all on drawing task performance. As shown in figure 4.18. mean performance on comprehension and text completion tasks is higher in the metaphor condition, but this interaction between task and metaphor is not statistically significant, $F(2,6)=0.95$, $p=.436$.

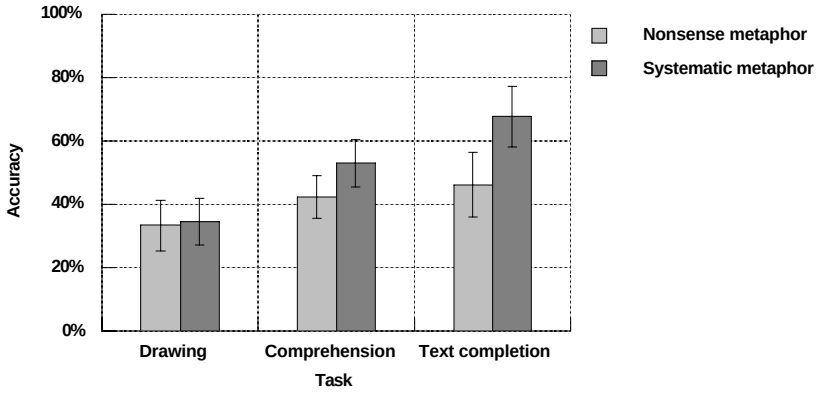


Figure 4.18. Effects of metaphor by task type for novices

Discussion

As in experiment 1, the performance measures used in this experiment provide a meaningful distinction between novice and expert performance which sets a reference point for the amount of benefit that metaphorical instruction provides to novices. Unlike experiment 1, experts did not perform these tasks significantly faster than novices. They did achieve far greater accuracy, however. In experiment 1 metaphor had little further effect on the performance of experts, and that finding was repeated here. The accuracy of the experts was near ceiling, however, so metaphor might have had more effect with a more difficult task. That possibility is not of great concern here, as this thesis concentrates on the benefit that metaphor can provide for novices.

The difference between novices and experts in this experiment may, however, have resulted as much from the fact that experts were better able to identify and ignore the nonsense metaphors – novices tended to spend more time on tasks for which they had been given nonsensical explanations. This effect is investigated in more detail in experiment 7, which compares systematic and nonsense metaphors to a further condition in which no metaphor is given at all.

The final point of interest in these results is the differences observed in performance for the diagram drawing task. Experts performed better than novices on this task – this may be a

result of the fact that experienced programmers are more accustomed to drawing diagrams, so their advantage arose from being comfortable and practised with similar tasks. In contrast, several of the experiments reported in the next chapter asked non-programmers to draw complete diagrams. The participants in those experiments often reported anxiety regarding their ability to draw.

In this experiment, novice performance in the drawing task was least affected of all the tasks by the provision of an explanatory metaphor. This may arise from the anxiety factor described above – the drawing task may have been subject to a floor effect, and a consequent reduction in the effect of metaphor, in the same way postulated earlier as arising from a ceiling effect in experts. Alternatively, participants may have relied on an uninterpreted visual image of the whole diagram, treating the drawing task as a short term visual memory problem rather than a comprehension problem. For novices using this strategy, a systematic metaphor would be less likely to have any effect on performance. The distinction between memory and comprehension, as well as between visual and relational components of diagrams, is investigated in far more detail in the experiments reported in chapter 6.

Chapter 5: Diagrams and Abstract Structure Generation

Those weird designs, they only show
What's going on in weirder minds,
Cause when you doodle then
Your noodle's flying blind.
Every little thing that you write
Just conceivably might
Be a thought that you catch
If while caught in a wink.
Doodling takes you beyond what you think
Then you draw what you feel.

Doodlin' – Horace Silver

The experiments described in the previous chapter found large differences in performance between experts and novices, but only small relative changes in novice performance as a result of using metaphorical notations. The apparent lack of educational benefits is disappointing. It is possible, however, that the notations used the wrong kind of metaphors.

In experiment 1, evidence from think-aloud protocols suggested that novice programmers paid little attention to implicit visual metaphors, yet regarded the problem in less abstract terms when using a physical metaphor. These findings concur with some of the intuitions of visual programming language designers and users – one of the themes that I found in the surveys of chapter 3 was the claim that visual languages would reduce the degree of abstraction required in programming. Diagrams may help users avoid abstraction by depicting an abstract concept in terms of physical experience (Lakoff 1993). Alternatively, diagrams may be more computationally tractable because they have less potential for expressing abstraction than symbolic languages (Stenning & Oberlander 1995).

We can thus distinguish between diagrams in which the components illustrate a simple physical metaphor, as in experiment 1 and 2, and diagrams whose geometric structure acts directly as an alternative concrete metaphor for some abstract structure. The latter is more like the case of an electrical schematic where the possible set of causal relationships is constrained by the connection paths in the diagram.

In experiment 1, participants appeared to use fewer abstract terms when using an overtly metaphorical pictorial notation. It is possible that an increased level of visual detail constrains the representation to refer to a specific situation, rather than an abstract set of potential situations. It is for precisely this reason that pictures have long been considered not to be abstract representations; Berkeley's early 18th century theory of vision (1705/1910) distinguished between the visible abstractions of geometry and perceptual experience of the

real world. Bartlett quotes Napoleon as distrusting the use of mental images: “those who form a picture of everything are unfit to command” (Bartlett 1932, p. 220). Modern work in cognitive psychology has also observed that mental image-based strategies are unable to represent indeterminacy (Mani & Johnson-Laird 1982), and that generalisation from multiple examples requires the translation of descriptions from images into verbal abstractions (Goldberg & Costa 1981) – the consequent loss of these visual-turned-verbal abstractions has been observed in psychiatric patients during left hemisphere ECT suppression (Deglin & Kinsbourne 1996).

The inability of mental images to support abstraction is considered by Stenning & Oberlander (1991, 1995) to be their principal advantage, because reducing the range of possible interpretations (they call this *specificity*) makes reasoning with a diagram more computationally efficient. Restricting the range of interpretations can also be a disadvantage, of course. Pimm (1995) believes that using concrete representations in mathematical settings may prevent children from forming necessary abstractions. Other theories, however, emphasise that mental images are at least more abstract than visual percepts because they do not specify all possible details (Paivio 1971, Miller 1993). This observation has also been made of representational conventions in drawing (Arnheim 1970) and of diagram use (Wang, Lee & Zeevat 1995).

If diagrammatic images are interpreted metaphorically, which of these possibilities would be the most relevant? The interpretation of metaphor is itself a process of abstraction from one situation to some interpretive domain (Verbrugge & McCarrell 1977, Gentner & Wolff 1997), but this abstraction makes metaphor difficult to understand because of the range of potential interpretations (Winner & Gardner 1993). If images could be used as intermediaries when interpreting metaphors (Beck 1978), this might provide the advantage of specificity – constraining potential interpretations. In fact, many theories of metaphor comprehension propose that mental images are central to use of metaphor (Cacciari & Glucksberg 1995, Gibbs & O’Brien 1990, Kaufmann 1979, Walsh 1990). Tentative proposals have been made of a functional relationship between the cognitive resources applied in diagram use and metaphorical image use (Lewis 1991, Lakoff 1993), but these have not been as confident as the claims made by computer scientists about the benefits of HCI metaphor.

The use of strategies based on mental imagery to solve verbal problems has historically been one of the central issues in the mental imagery debate. Much of the existing research into diagram use appears to have been motivated by entrenched positions in that debate, as reviewed by Blackwell (1997b). This discussion can only briefly summarise that review, which considered experimental tasks involving picture naming (e.g. Potter & Faulconer 1975), identity judgements (e.g. Theios & Amrhein 1989), evaluating sentences about diagrammatic

situations (e.g. Clark & Chase 1972) and problem solving (e.g. Frandsen & Holder 1969, Schwartz 1981). Blackwell also reviewed the main theoretical positions in the debate (Kieras 1978, Pylyshyn 1981, Kosslyn 1981) and some of the philosophical approaches to resolving it (Dennett 1981, Goodman 1990, Sloman 1995).

The most convincing evidence in the imagery debate has come from purely visual tasks such as mental rotation (Shepard & Metzler 1971) and map construction (Kosslyn, Ball & Reiser 1978), but many experiments have investigated the diagrammatic use of images to represent logical propositions (Huttenlocher 1968, Shaver, Pierson & Lang 1974/75, Mani & Johnson-Laird 1982, Fuchs, Goschke & Gude 1988, Matsuno 1987). Many computational models of mental imagery have been constructed as supporting evidence that images can be used for logical reasoning (Lindsay 1988, Greeno 1989, Glasgow & Papadias 1995), as well as for reasoning about the abstract structure of physical situations (Koedinger & Anderson 1990, McDougal & Hammond 1995, Novak 1995, Gardin & Meltzer 1995, Forbus 1983, Faltings 1987, Blackwell 1989).

The most ambitious claims found in the surveys of chapter 3 extend well beyond such restricted problem-solving activities, however. Some researchers apparently claim that all software design problems are solved by thinking in images, and that visual programming languages directly facilitate the solution process. This intuition is consistent with the introspections of programmers who use conventional languages (Petre & Blackwell 1997). Several other studies have also found evidence for use of mental images during software design (Gilmore & Green 1984a, Buckingham Shum et. al. 1997, Green & Navarro 1995, Saariluoma & Sajaniemi 1994).

When mental images are reported by expert programmers, the activities they refer to are not simple problem-solving, but large-scale design. The processes of system design in programming have more in common with other design disciplines, such as engineering and architecture, than with the type of experimental tasks described earlier in this review. Ferguson (1992) has described the way in which the development of modern engineering depended on the ability to publish pictorial representations of engineering designs. Ferguson, along with many eminent engineers whom he quotes, believes that engineering designs are constructed as mental images, and that communicating those designs depends on non-verbal representations. Similar claims have been made regarding the use of visual representations in architecture. Goel (1992, 1995) challenges the computational theory of mind on the basis that it cannot account for the way that architects use sketches, as documented in protocol studies of architects at work by Goldschmidt (1991, 1994) and Suwa and Tversky (1997). Fish and Scrivener (1990) have proposed a general model of the use of sketches in creative

design – they claim that perception of sketches interacts directly with mental imagery to enable creative problem solutions.

The use of both visual representations and mental images to discover creative solutions has also been proposed as a fundamental mechanism of scientific discovery (Dreistadt 1968, Gooding 1996, Nersessian 1995, Qin & Simon 1995), as well as in other fields of creativity (Koestler 1964, Shepard 1978, Johnson-Laird 1988). It has even been proposed that almost all problem solving involves structural analogies constructed from mental images (Paivio 1971, Kaufmann 1979). Recent experimental investigations of this proposal have concentrated on a single question, however: once a mental image has been formed, is it possible to reinterpret this image in order to discover new properties? This question is crucial to proposed models of image-based creativity, and highly relevant to the theories of engineering and architectural design described above. Finke, with various colleagues, has carried out a series of experiments in which he has found evidence for discovery of new structure in images when subjects are shown apparently unrelated elements, then asked to combine them in working memory (Finke & Slayton 1988, Finke, Pinker & Farah 1989, Finke 1996). Other experiments, however, have found that memorised ambiguous images cannot be reinterpreted, although the subject can later reproduce the image on paper and then reinterpret their own drawing (Chambers & Reisberg 1985, Slezak 1992, Walker et. al. 1997).

The experiments in this chapter investigate the way that diagram use interacts with mental imagery during design tasks. It addresses several of the questions that have been discussed in this introduction, but concentrates on their relevance to diagram use, rather than speculating on general properties of mental images.

Experiment 3: Visual imagery during planning

Is there any evidence that diagrams are direct expressions of image-like mental representations? One way to investigate this question is by analysing external signs of cognition associated with both diagrams and imagery. Brandt and Stark (1997), for example, found that the same sequence of gaze fixations was involved in imagining a simple diagram as in observing it. A second alternative is to use dual-task studies: if a certain task has been observed to impair the formation of mental images (presumably, but not necessarily, because it uses the same cognitive resources), will that task also impair the planning of diagrams? This experiment takes the second approach; if diagram planning is impaired by the secondary task, we can infer that diagrams express image-like mental representations.

It also addresses two further questions arising from experiment 1 by using tasks that may involve different encodings in working memory. The first is related to the possible distinction between physical information and abstract information. Experiment 1 suggested that pictorial representations may cause physical information to be emphasised rather than abstract information. Previous research into working memory has found experimental and neurological evidence that spatial information is encoded separately from categorical information (McNamara 1986, Mecklinger & Muller 1996, Kosslyn et. al. 1989) but also that the two are combined when abstract information must be memorised in association with a spatial context, as when functions are assigned to buildings on a map (McNamara, Halpin & Hardy 1992). It seems likely that visual material presented in diagrams involves both categorical and spatial information. Must a combination of abstract information within a spatial metaphor hence rely on different working memory resources?

The second working memory question arising from experiment 1 is the distinction between encoding the spatial arrangement of the elements in a diagram and encoding their visual appearance. Just as there is strong evidence for separate working memory resources for categorical and spatial information, there is also substantial evidence for a distinction between the visual and spatial components of working memory, including neurological (Farah et. al. 1988), developmental (Logie & Pearson 1997), anatomical (Mishkin, Ungerleider & Macko 1983) and functional imaging (Smith & Jonides 1997) studies, as well as evidence from conventional cognitive experiments. An example of the latter is the report by Tresch, Sinnamon and Seamon (1993) that memory for objects or for location is selectively impaired after tasks involving colour identification and motion detection respectively. In experiment 1, the mental animation process that was postulated as a basis for analysing pictures of a physical machine can be identified as primarily visual, while the process of arranging nodes and connections into a complete diagrammatic solution is primarily spatial.

There is a diverse spectrum of hypotheses relating the two distinctions: coordinate/categorical and spatial/visual. It is quite possible that there is only a single representational dichotomy, but that it is simply poorly understood. Either distinction, however, may be relevant to the current investigation – the distinction between abstract and physical information, or between pictorial metaphor and simple geometry, might easily interact as a result of their respective working memory requirements. This experiment addresses these questions by considering separately abstract and physical situations, and by using separate secondary tasks that exercise either visual or spatial short term memory.

Notation

The notation used in this experiment was designed to be as simple as possible while maintaining the visual dataflow metaphor introduced in experiment 1. It was intended for use by participants with no experience of computer programming, without requiring that they learn any computational concepts. The form of the notation was nodes connected by arcs, as in experiment 1, but these were given only minimal semantics. Four different types of node were defined, but these had no semantic implication – I told participants that they could choose whichever node they liked, and use them to stand for anything they liked. Each node type included a selection of terminals to which arcs could be connected. Terminals on the left hand side of a node were described as "inputs", and those on the right hand side as "outputs", so that flow implicitly proceeded from left to right, even though (as in experiment 1) I never explicitly mentioned flow. Each terminal could have any number of arcs connected to it.

As in experiment 1, there were two forms of this notation, each with identical semantics, but with different pictorial images representing nodes and arcs. The first of these used simple geometric shapes, connected by plain lines, shown in figure 5.1.

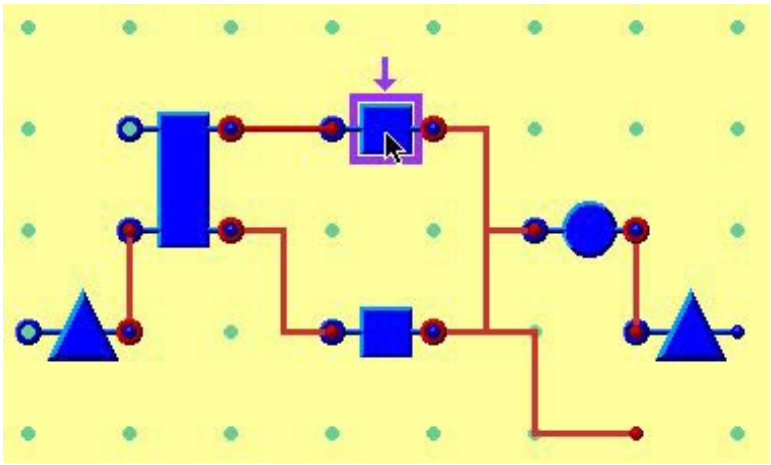


Figure 5.1. Simple geometric nodes and arcs

In the second form of the notation, nodes were connected together by images of cylindrical ducts (actually miniaturised bitmap images produced from digitised photographs of air-conditioning ducts). The nodes themselves were also small photographic images, designed to be obviously mechanical, and plausibly producing flow through the attached ducts, but without having any identifiable function. They were produced from digitised photographs of air conditioning components and garage tools, but the original devices would only be

identified by an experienced engineer – participants in the experiment did not recognise them. This implicit data flow version is shown in figure 5.2.

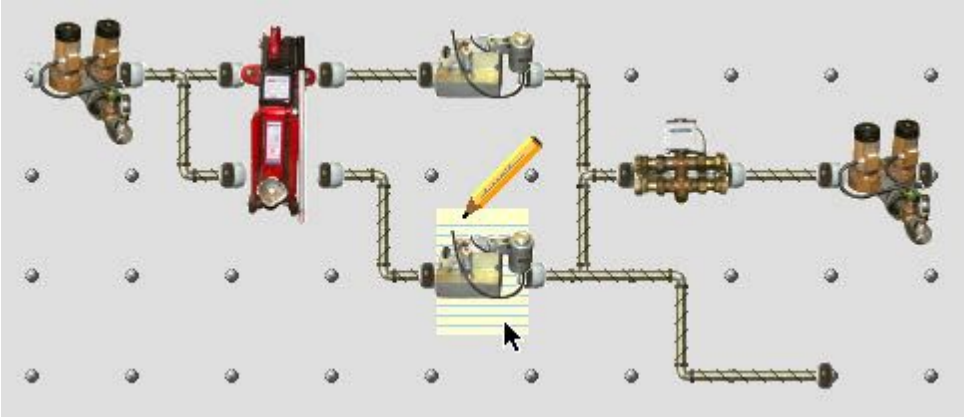


Figure 5.2. Mechanical nodes and arcs with implicit data flow

Participants created diagrams by manipulating the appropriate set of nodes with an editor on a computer screen. The editor screen is illustrated in Figure 5.3. The editor included a palette in one corner with four different node images; participants created new nodes by clicking on any one of these images with the mouse. Nodes could be moved to any location on the screen by clicking in the middle of the image, and dragging it. Connections between nodes could be made by dropping one node so that its input coincided with the output of another node, or by clicking on the output of one node, and dragging from there to the input of another node. If the node at either end of a connection was dragged to a new location, the arc would move to follow it.

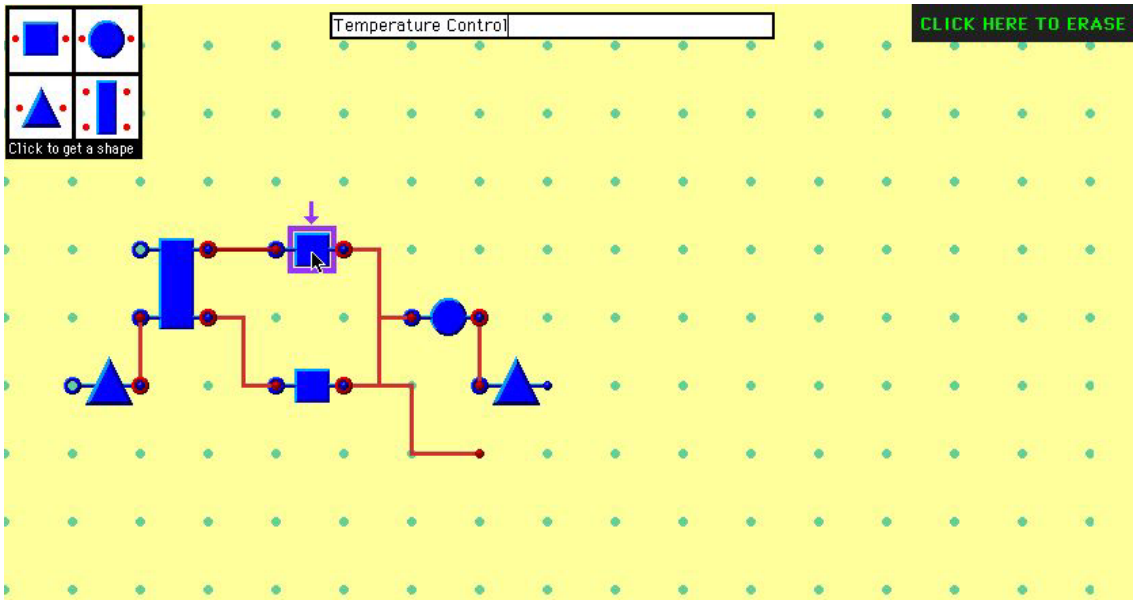


Figure 5.3. Simple node and arc editor

Most participants in this experiment had little experience of computers, and some had never used a mouse before. To make it easier to arrange nodes and connect them together, the screen was therefore divided into a grid of points with approximately 1 cm spacing, as shown in Figure 5.3 (for the geometric version, the grid was simple dots, while for the pictorial version, it resembled a grid of rivet heads on a steel plate). When a node was moved to a new position, it would "jump" to the nearest location on the grid. This made it relatively easy to connect terminals together – the participant only needed to click within the 1 cm^2 region around the terminal.

The editor also included an "erase mode" allowing nodes or arcs to be removed (the erase mode button is at the top right of figure 5.3). If the participant moved the mouse cursor over any shape on the screen after selecting erase mode the shape would turn into a cloud containing the words "click me"; clicking would then erase it. When not in erase mode, clicking on a node caused a selection box to be drawn around that shape. For the geometric version, this was a simple box and arrow, and for the pictorial version, it was a piece of paper and a pencil. The participant could assign a label to each node by clicking to select it, and then typing the label. Labels were only required after the diagram was complete, however, as in experiments by Szlichinski (1979).

These various features of the diagram editors are illustrated in appendix B.3.

Tasks

Participants were asked to use the editor to draw diagrams describing the workings of six different devices. Three devices incorporated moving parts and *physical* processes, while the other three had no internal moving parts, and only *abstract* processes. Table 5.1 shows the six devices used and the categories they were assigned to.

Concrete	Abstract
washing machine	telephone
motorbike	calculator
coffee vending machine	television

Table 5.1. Abstract/concrete devices

Participants were told that the diagram should show the way that the named device worked on the inside, and should not be a picture of the device.

Participants were also asked to perform secondary tasks while planning their diagrams. The first of these tasks, *spatial tracking*, was designed to interfere with spatial working memory, as in the motion detection task described by Tresch et. al. (1993). The participant moved the mouse pointer to follow a circle moving slowly around the computer screen with random changes in direction. If the mouse pointer moved outside the circle, the circle changed colour – the participant was instructed not to let this happen (more positive alarms were also tried, but were found during pilot testing to induce excessive anxiety). The exact form of this task was proposed by Professor Alan Baddeley (personal communication 18 June 1996). The second task, *visual noise*, has been shown by Quinn and McConnell (1996) to interfere with memory for a list of items specifically when subjects are asked to use a visual mnemonic strategy. The participant watched a continually changing random grid of black and white squares. In the third task, *blank screen*, the participant simply watched a blank screen with a fixation cross in the centre.

Equipment

The editor was implemented using the animation package MacroMedia *Director*, version 4.0. I captured the pictorial node and arc images using a Kodak DC500 digital camera, reduced the resolution to 40 pixels square using Adobe *Photoshop*, and edited them to provide uniform connection points on each node before importing them as bitmaps for use in

Director. The animated behaviour of the nodes and arcs in response to user actions was implemented in the *Lingo* scripting language provided with the Director product.

The experiment procedure was controlled by a presentation sequence implemented in Director. This provided an animated tutorial demonstrating the use of the editor (the tutorial script is reproduced in appendix B.3), then invoked the editor program. The editor program maintained a log of all actions made by the participant, with the system time (reported as the previous whole second) recorded at the time of each action. The experimental software ran on a Macintosh PowerPC 8200/120 computer with a 17 inch monitor displaying a resolution of 832 x 624 pixels at 24-bit colour.

The secondary tasks to be performed while planning diagrams were also implemented as movies in MacroMedia Director. The spatial tracking task was designed to have minimal visual contrast. A dark grey circle slowly followed a randomised path over a light grey field. The speed of motion was kept constant, with the direction of motion changing by small randomised increments. As long as the mouse pointer was kept over the top of the moving circle, it would stay the same colour, but if the participant let the pointer move away, the circle would change to a slightly different shade of grey.

The visual noise task was based on a C program originally developed for the IBM PC by Jean McConnell (McConnell, personal communication 26 July 1996), as used in the research described by Quinn & McConnell (1996). The original program was not reused, but I created a close visual equivalent using the facilities of Director. I first wrote a LISP program to generate a series of images consisting of a grid of black and white squares. In each image the squares of the grid were randomly coloured either black or white. These images were then imported as a sequence of animated frames in Director, with the transition between frames taking place as a random fade, where the fade grid corresponded exactly to the grid of random squares. The result of this was a randomly changing sequence of grid squares practically indistinguishable from the stimulus used by Quinn and McConnell.

Hypotheses

1. Based on the inhibitory effect of pictorial representations on reasoning about abstract tasks observed in experiment 1, the same effect should result in an interaction between the type of editor and the type of device being explained.

2. On the basis of the previous literature describing use of mental images, introducing a secondary task that has been shown to impair visuo-spatial short term memory would inhibit planning of the diagram.

3. That abstract and concrete diagrams might be prepared as different image types, and that different secondary tasks would therefore have different inhibitory effects on planning each device type, possibly interacting with the two types of editor.

Participants and design

Twenty-four participants were recruited from the APU panel of volunteers. None of them had any experience of computer programming. Two further participants were recruited after two of the original cohort misinterpreted the description of the editor palette, concluding that each diagram should have exactly four nodes.

One independent variable was assigned randomly between subjects – twelve participants used the editor with simple *geometric* shapes and twelve used the *pictorial* editor with implicit data flow. A second independent variable was the nature of the diagram drawing task. Each participant drew six diagrams, three of which explained *physical* processes and three *abstract* processes. The third independent variable was the secondary task performed by the participant while planning each diagram: *spatial tracking*, designed to interfere with spatial working memory, *visual noise*, designed to interfere with visual working memory, and *blank screen*, in which the participant simply watched a fixation cross in the centre of an otherwise blank screen.

The experiment included three dependent variables. The first was the degree of *elaboration* – the number of nodes in the diagram, as measured in experiment 1. The second was the *speed* with which the diagram was created – the average interval between addition of new nodes or arcs. The third was the proportion of *changes* made to the diagram – the proportion of nodes or arcs that were moved or erased after their initial creation.

In order to test the hypothesis of an interaction between the type of editor and the type of process being explained, I tested for different degrees of diagram elaboration for each device type in the two groups. In order to test the second hypothesis, that the secondary tasks would inhibit planning, I compared the speed of creation of the first ten additions to the diagram immediately after the end of the planning period. I also compared the proportion of changes made to the diagram. The third hypothesis of an interaction between the type of secondary task and the pictorial representation or process type was tested in terms of diagram elaboration.

Procedure

The experiment started with an explanation of the editor functions, at a pace controlled by the participant. The first part of the explanation covered basic mouse operation – clicking on a shape and dragging it from one place to another. This was followed by an animated demonstration of the editor functions, using the appropriate (*geometric* or *pictorial*) version of the editor. The secondary tasks were then demonstrated, so that the participant could practise following the moving circle, and see the random grid display. Finally, the participant was asked to draw a diagram as a practise exercise using the editor. The instructions for the exercise specified that the diagram should show how a toaster works on the inside. It stressed that the diagram should not be a picture of a toaster, and that it did not need to look like any part of a toaster – it would simply show how a toaster worked. No further instructions were given regarding the intended use of the nodes and arcs.

During this instructional sequence, I sat beside the participant, and answered any questions asked by the participant. Most participants had no questions. Some needed assistance with the procedure for dragging using the mouse. Some asked for clarification of the difference between an input terminal of a node and an output terminal. Some asked for clarification of the instruction that the diagram should show how the toaster works, rather than what it looks like. Several participants were quite anxious about the task, and protested that they would be unable to draw any diagrams. I reassured these participants in general terms, and all of them proved able to draw acceptable diagrams using the editor – it was not necessary to remove any participants as a result of inability to use the editor.

During the remainder of the experiment, participants worked on their own, drawing diagrams to describe the workings of the six different devices. The presentation sequence displayed a description of the required diagram, including a reminder that the diagram should show the way that the named device worked on the inside, and should not be a picture of the device. The participant was then given 60 seconds to plan their diagram, during which they had to perform one of the three secondary tasks. The allocation of secondary task to device description was balanced across subjects, and the presentation order of both devices and secondary tasks was also balanced.

After the planning period, the editor screen was displayed. The participant then had a period of five minutes in which to draw the diagram they had planned. At the end of the five minutes, they were given a further two minutes in which to type labels for each node in the diagram. During this second period, the node creation and erase functions were disabled. This planning / drawing / labelling sequence was repeated six times by each participant.

When participants had completed the diagram drawing tasks, I asked them to complete a debriefing questionnaire. This questionnaire asked:

- how easy it was to plan the diagrams in advance;
- which was the most difficult diagram to plan;
- whether they felt that the secondary task had made the diagrams more difficult to plan;
- how they decided which shapes to use;
- whether shapes were chosen during planning, or only while drawing the diagram; and
- whether they had been able to assign names to shapes in advance.

Results

The analysis approach is a multivariate analysis of variance (MANOVA) with repeated measures, having two within subjects factors (abstract/concrete processes and blank screen/visual noise/spatial tracking secondary task), and one between subjects factor (geometric/pictorial editor). The three dependent variables were elaboration (number of nodes), initial speed of production, and proportion of diagram elements changed. The MANOVA results reported here are calculated using Pillai's Trace method; alternative MANOVA techniques did not result in any difference of significance values.

Initial univariate tests showed that both the editor type and the type of process had significant effects on elaboration $F(1,22)=5.74$ and 5.81 respectively, $p<.05$. As shown in figure 5.4, *abstract* processes were drawn with more nodes (an average of 8.74) than were *concrete* processes (7.90). Diagrams drawn with the *geometric* editor were also more elaborate (9.46 nodes) than those drawn with the *pictorial* editor (7.18 nodes). The hypothesised interaction between these two factors did occur in the predicted direction – diagrams describing *abstract* processes were more elaborate when using the *geometric* editor. Although the difference in the means was relatively large, this interaction was not significant $F(1,22)=2.33$, $p=.14$. A similar interaction effect was observed for the other dependent variables. Participants constructed the diagram more quickly when using the *geometric* editor for *abstract* processes, and they made a smaller proportion of changes to their diagrams, as shown in Figure 5.5. MANOVA analysis indicates that these interactions when taken together are significant, $F(3,20)=5.77$, $p<.01$.

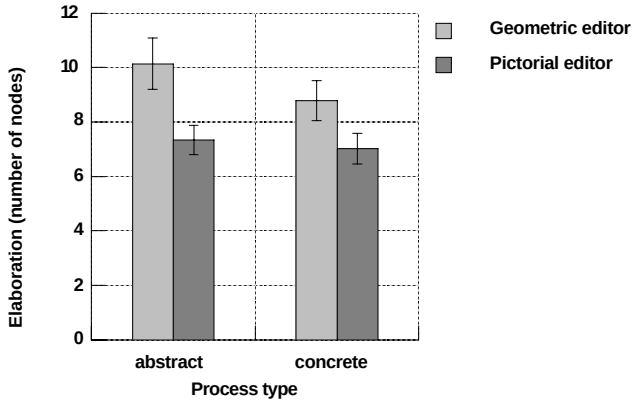


Figure 5.4. Effects of editor type and process type on diagram elaboration

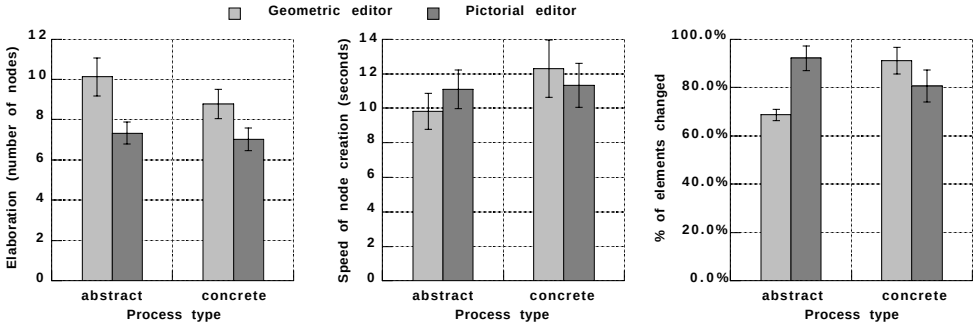


Figure 5.5. Interactions of editor type and process type:
elaboration, speed and number of changes, taken together, show a significant effect.

The second hypothesis was that secondary tasks during the planning period would have an effect on speed of production and the proportion of changes made. There was no evidence that the secondary task had any effect on either speed of production $F(2,44)=0.034$, $p=.96$ or on proportion of changes $F(2,44)=0.116$, $p=.89$. There was also no evidence of the interactions postulated in the third hypothesis – a multivariate analysis of variance found no interaction of secondary task with process type $F(6,86)=1.373$, $p=.51$ or with editor type $F(6,86)=0.562$, $p=.21$. Univariate ANOVA tests on each variable also found no significant interactions with the secondary task.

When answering the questions in the debriefing questionnaire, only five of the 24 participants said that they had been able to choose shapes in advance while planning the diagram, although a further six said that they could do so occasionally. Twelve of the participants said

that it was “not easy”, “hard”, “difficult” or “impossible” to plan diagrams in advance. The performance of these twelve was then considered separately from the twelve who reported that advance planning was relatively easy. As can be seen in figure 5.6., there was no overall difference between the performance of the groups in any measure, with the MANOVA test result $F(3,20)=0.425$, $p=.73$. There were however marginally significant covariances of self-reported planning with the effect of secondary tasks, $F(6,82)=2.074$, $p=.065$. Those who reported that it was easy to plan in advance actually performed slightly better (more elaborate diagrams and faster production) when carrying out secondary tasks, while the reverse was true of those who had difficulty planning.

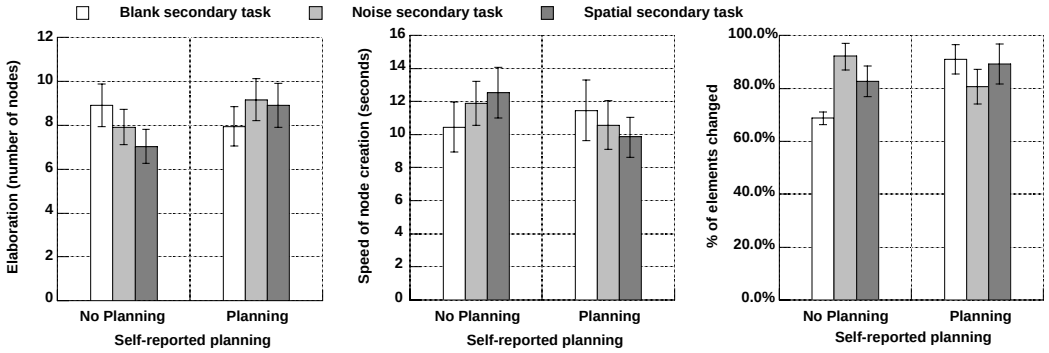


Figure 5.6. Effect on performance of self-reported advance planning

Discussion

As in experiment 1, there is evidence in this experiment that novices are not completely happy when asked to use pictorial elements diagrammatically. In experiment 1, several participants commented that they found the level of detail in the pictorial notation confusing. At the end of the experiment I showed some of these participants the geometric version of the language, and they claimed that they would prefer to use that version. I also showed two of the participants in the geometric condition the pictorial version, and they said that they would prefer not to use it. This supports the finding of Strothotte and Strothotte (1997), amongst others, who have noted that pictogram users tend to choose more “abstract” symbols such as asterisks or arrows when representing abstract concepts.

In this experiment, the informally expressed preference has been supported by performance measures. Participants were less productive when using a pictorial metaphor to create

diagrams than when using simple geometric shapes. This difference was most pronounced in the case of diagrams describing abstract processes. My explanation for this is that participants regard the illustrations as being literal rather than metaphorical, and that this results in incongruity between the task and the notation. No participants commented that they found the pictorial notation inappropriate for particular tasks, but this hypothesis is tested in greater detail in experiment 5.

The main intention of this experiment, however, was to test the way in which choice of notation affects the user's ability to form diagrams as mental images. Only some participants in this experiment appeared to carry out any planning using mental imagery. Secondary tasks during the planning period had no overall effect on speed of production, despite the fact that these tasks have reliably been shown to impair mental images in short term visuo-spatial memory. Those participants who reported that they found it easy to carry out advance planning actually improved their performance when a secondary task was given. It is possible that the plans involved verbal rehearsal rather than images – this is investigated further in experiment 6B, in which some participants were given no planning time at all.

Overall, this experiment found a reduction in performance when pictorial elements were used to describe abstract processes. A further relationship had been expected between performance and the use of mental images for diagram planning, but no clear evidence was found for this.

The different reports regarding advance planning reflect a wider range of individual differences that are relevant to this experiment. The underlying causes of these differences may be complex. Several researchers have reported differences in mental imagery ability correlated with gender (Casey 1996, Delgado & Prieto 1996, Paivio & Clark 1991, Silverman, Phillips & Silverman 1996), handedness, or an interaction between the two (Halpern 1996). Further proposed distinctions include the difference between verbalizer and visualizer "cognitive styles" (Richardson 1977), interaction of cognitive style with handedness (Casey et. al. 1993), cognitive style with gender (Winner & Casey 1992), with age (Johnson 1991) or self reported vividness of mental imagery (Katz 1983). This is a very complex issue, and I found no obvious correlations with (for example) gender in post hoc tests. It is certainly true that there was a wide range of individual variation in performance in this task, and this variation has contributed to the marginal significance of the reasonably large effects observed. Stenning and Gurr (1997) have also observed the difficulty of evaluating external representation use in the face of individual differences such as these.

Van der Veer (1990) has explicitly investigated the effect of cognitive style on the interpretation of software diagrams, but found that individual differences in mathematical experience had a greater effect than cognitive style. Previous experience of mathematics

notations has also been identified as a factor in image memory by Winner and Casey (1992) and by Manger and Eikeland (1998). Most of these studies have also noted an interaction of experience with gender or gender image. This is in accordance with casual comments made by many of the female participants in this and later experiments, along the lines of "I'm not much good with mathematical things – you should have got my husband/son to do this experiment".

Experiment 4: Comparing diagrams to text

Participants in experiment 3 were selected on the basis that they had no experience of computer programming – indeed most had little experience of computers, and some had never used a mouse before taking part in the experiment. The training phase did take account of this, and all participants successfully completed the experiment. Nevertheless, the environment was not one with which they were comfortable. This may have caused participants to produce diagrams that were unusually simple. The use of a computer-based editor may also have removed the potential in pencil sketches for discovery through ambiguity, as has been suggested by Goel (1995) in the case of architectural CAD systems. In this related experiment, participants were therefore asked to explain the same devices, but by either drawing diagrams using pencil and paper or writing a verbal explanation.

Notation

This experiment retained the minimal prescription of semantic interpretation as in experiment 3. Participants were instructed to construct diagrams by drawing simple shapes and connecting them together with arrows, as if each shape had inputs and outputs. The instructions included three examples of what this would look like – these are reproduced in figure 5.7 (a full reproduction of the instructions is included in appendix B.4). As in experiment 3, participants were given no further guidance regarding how nodes or arcs should be interpreted. Participants were asked to write labels next to each shape, but only after all the shapes in the diagram had been drawn.

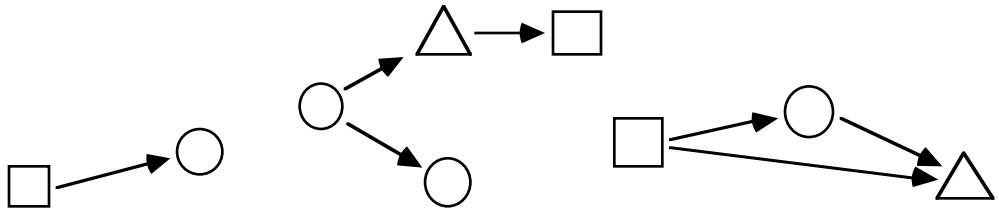


Figure 5.7. Examples of shapes connected by arrows

In a second notational condition, participants were asked to describe devices by "writing an explanation in words". No further constraints were given, other than the constraints of time, and of scale implicit in the size of the paper provided.

Tasks

Participants in this experiment were asked to describe the same six devices introduced in experiment 3, divided in the same way into three that involved *abstract* processes and three involving *physical* processes.

Equipment

In order to encourage free production of diagrams, participants worked with pencils rather than ink pens. They were not given erasers, however, so that there would be a clear record of any changes they made to their productions. Both the diagrams and the written descriptions were produced on A3 sized sheets of paper. I used a stopwatch to allocate the amount of time provided for each task.

Hypotheses

1. That the use of pencil and paper would allow participants to be more productive, resulting in more elaborate diagrams than those produced in experiment 3.

2. That written descriptions would be more suitable for describing abstract devices, and that those descriptions would be more elaborate than when abstract devices were described with diagrams.

Participants and design

Six participants were recruited from the APU volunteer panel. There were no factors varied between subjects, and two independent variables within subjects. The first independent variable was the instruction to explain devices either by drawing a *diagram*, or by writing *text*. The second independent variable was the nature of the devices. The use of three devices of each type, but only two conditions of the first independent variable, produced an unbalanced design. It was therefore not possible to test directly for interaction between the two factors.

Two dependent variables were measured. The first was the number of *referents*. This was established in diagrams by counting the number of nodes, and in text by counting the number of noun phrases that referred to independent entities. The second dependent variable was the number of *relations*. This was established by counting the number of arcs in diagrams, and the number of phrases describing any relationship between two referents in the text.

The first hypothesis concerned elaboration relative to experiment 3. It was tested by comparing the number of nodes in experiment 3 to the number of referents described in this experiment. The second hypothesis regarding interaction of writing with abstract device type was measured in terms of the number of referents and relations.

Procedure

The experimental material was assembled into a booklet, and participants simply worked through this booklet in the order it was constructed. The instructions started with:

> **General Instructions**
>
> In this experiment, you will be asked to explain what happens inside some thing that might be used around the house. You will be asked to explain what happens either by drawing a diagram, or by writing your explanation in words.
>
> **Written Explanations**
>
> When you are asked to make an explanation in words, you can choose whatever way you prefer to write the explanation.
>
> **Diagram Explanations**
>
> When you are asked to make the explanation using a diagram, you should make the diagram by choosing simple shapes and joining them together with arrows. The shapes you use should be quite simple – they don't have to look like anything in particular.

After these instructions, the participant completed a practice exercise, drawing a diagram that shows what happens inside a toaster. A further page of instructions then repeated the

instruction that the diagram should "use simple shapes connected together with arrows" and "does not have to look like the thing you are explaining".

Six separate pages of instructions then followed – each naming one of the six devices, and specifying whether the explanation should be a diagram, or written text. Each page of instructions was followed by a blank A3 page on which to draw the diagram or write the text. I restricted the time available both for planning the explanation, and for producing it. The participant was not allowed to start drawing or writing for one minute after reading each instruction – they were told that this time was to be used for planning. At the end of the minute, they were then given three minutes in which to complete the task.

Results

There were two different measures of diagram complexity in this experiment: the number of referents in descriptions, and the number of relations described between them. This was intended to distinguish diagrams that contained the same number of nodes, but were more topologically complex, as there is evidence that this type of complexity may not be represented as a simple image – Chechile et. al. (1996) report that recall of paired associate network diagrams is poorer for more complex diagrams, even when all other aspects of image complexity are rigorously controlled. In fact, only 6 of the 36 descriptions produced in this experiment included more than the minimum number of relations needed to connect all the referents. The numbers of referents and relations are therefore very highly correlated (r=.848, p<.001), with no significant difference (Z=0.52) between the correlation found in diagram descriptions (r=.898) and in text descriptions (r=.854). The remainder of this analysis therefore uses number of referents as the sole measure of elaboration.

My main concern in designing this experiment was to test whether the editors used by participants in experiment 3 might have reduced their productivity in terms of diagram elaboration. I therefore compared the number of nodes contained in diagrams produced in experiment 3 to the number of referents contained in the diagram and text productions of experiment 4. The mean elaboration in experiment 3 was 8.3 nodes, and in this experiment was 8.8 referents. This difference is not statistically significant, whether or not the distributions of the two experiments are assumed to have equal variances, $t(52.6)=.738$, p=.46. The same devices were described in both experiments, and there was no significant difference in the overall level of elaboration for each device, $F(5,174)=1.185$, p=.318. There was a large difference between the two experiments for two of the devices, however. As shown in Figure 5.8, the calculator description was less elaborate in this experiment, and the motorbike description was more elaborate, $F(12, 168)=84.4$, p<.001.

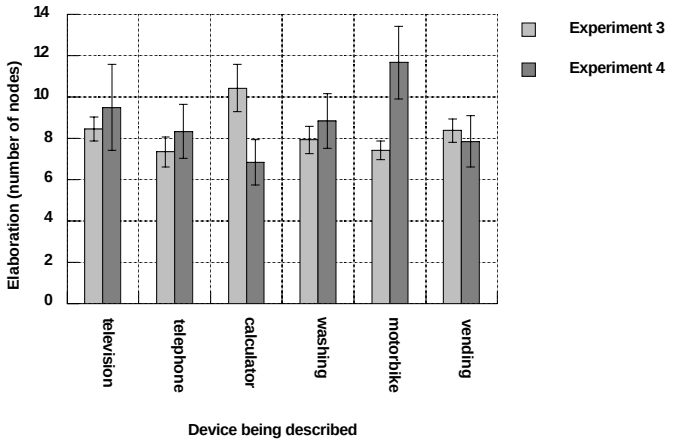


Figure 5.8. Elaboration of device descriptions in experiments 3 and 4

The second hypothesis was that text descriptions would be more suitable for describing abstract devices. As described above, the unbalanced design of this experiment does not allow a repeated measures analysis of this hypothesis. I therefore analysed the complete set of 36 descriptions produced in this experiment as independent observations. Text descriptions did contain more referents than diagrams, as shown in figure 5.9. This effect was statistically significant, $F(1,32)=12.65$, $p<.01$. There was not however any significant interaction between the form of the description and the type of device, $F(1,32)=0.093$, $p=.762$.

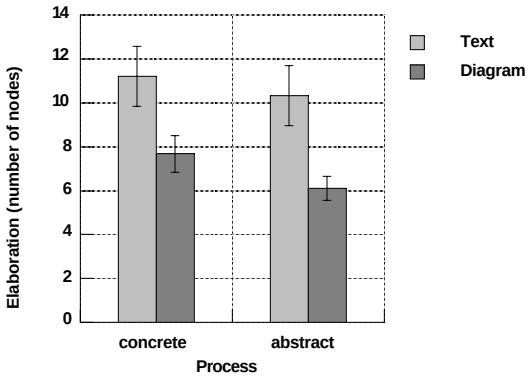


Figure 5.9. Text and diagram descriptions of abstract/concrete devices

The text descriptions produced in this experiment, if considered as an independent group, appear to have a slightly higher level of elaboration than the diagrams produced in experiment 3 (this is shown in Figure 5.10). This demonstrates that other members of the same volunteer population do know more about the six devices than participants in

experiment 3 chose to include in their diagrams, $t(160)=2.67$, $p<.01$. The diagrams produced with pencil and paper in this experiment do not however differ significantly in their degree of elaboration from those produced in experiment 3, $t(178)=0.75$, $p=.453$. This suggests that the computer editors used in experiment 3 did not inhibit diagram elaboration any further than plain pencil and paper do.

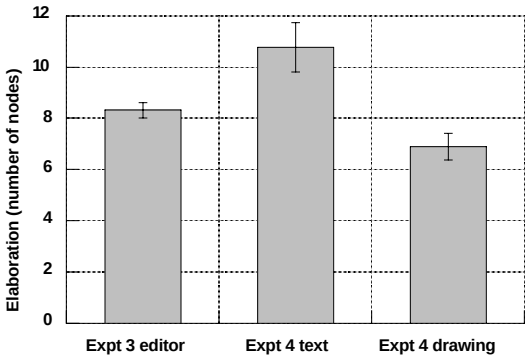


Figure 5.10. Text and pencil diagrams compared to experiment 3

Discussion

On the basis of these results, it is possible to discount some potential confounds in experiment 3. Firstly, there is no evidence that participants in experiment 3 were especially affected by the use of a computer to draw diagrams – in fact, their diagrams were more elaborate than those produced simply with pencil and paper. Secondly, there is no evidence that participants in experiment 3 were constrained by not knowing enough about the devices being explained – members of the same population were easily able to supply more information about the devices (but in text) than others had done in their diagrams.

This difference in elaboration between text and diagrams has disturbing implications for those who claim that diagrams are "intuitive" in some sense. In a previously published paper I have reported the difference in mean elaboration found in this experiment as "Correction: A picture is worth 84.1 words" (Blackwell 1997a). A more intriguing observation is that part of the difference in elaboration between text and diagrammatic descriptions comes from the fact that participants generally included either themselves or a third person as an actor in their text descriptions. Diagrams describing the same operations almost never included an actor as a node in the diagram. Further investigation of this observation is beyond the scope of this thesis, but it may be of interest when pragmatic conventions of diagram use are studied in the context of applied linguistics (e.g. Oberlander 1996). This observation only accounts for a

maximum mean difference of one between the number of referents in text and diagrams; even when subtracting one from the text counts, there is still a significant difference between the level of elaboration in text and diagrams, $t(34)=2.67$, $p<.05$.

One further observation can be made about these results on the basis of other research into drawing. Although participants in experiment 3 may have found computerised diagram editors uncomfortable to use, most people also have a very restricted repertoire of representational devices that are available to them when drawing (van Sommers 1984, Edwards 1979, Thomas & Silk 1990, Karmiloff-Smith 1990). In this experiment participants were instructed to use specific symbols in ways that were possibly remote from their usual habits of drawing. The basic elements were only lines and simple shapes, but these do have conventional pictorial implications – whether because of fundamental perceptual mechanisms (Kennedy 1975) or depictive conventions (Willats 1990). On the other hand, most people normally produce even supposedly representational drawings as semi-diagrammatic arrangements of conventional pictorial symbols rather than using a naturalistic style. Snyder and Thomas (1997) propose that these diagrammatic drawings simply reflect efficient abstract codings of the environment, a facility that is absent in the highly naturalistic productions of autistic children (Selfe 1985, Scott & Baron-Cohen 1996). The interaction between diagrammatic and depictive conventions may provide some explanation for the fact that the hand drawn diagrams of novice diagram users in this experiment were less elaborate than either those produced with computers or written text, but firm conclusions would require further investigation beyond the scope of this thesis.

Experiment 5: Use of incongruent pictorial nodes

I suggested in the discussion of experiment 3 that the interaction of mechanical and geometric pictures with explanations of abstract and concrete devices may simply result from a perceived incongruity between the task and the notation. Everyone knows that pocket calculators do not contain moving parts, so it requires more imagination to describe one using photographs of complex machinery. Carroll and Thomas (1982) have noted that this type of incongruity can compromise the use of physical metaphors for computer systems. Many theories of metaphor claim that metaphors are made more apt when there is greater separation between source and target domains (e.g. Tourangeau & Sternberg 1982), but this has been challenged by Heydenbluth and Hesse (1996), who found that analogical problem solutions were less elaborate when the source and target domains were dissimilar, even though the problem was structurally identical to another relating similar domains.

In order to test this hypothesis, I carried out a further experiment along the same lines as experiment 3, but with even greater incongruity between the notations provided and the devices to be described.

Notation

This experiment is based on the same diagram editor program that was used in experiment 3. Experiment 3 used two different versions of this program: in the first the nodes were simple geometric shapes and the arcs were unadorned lines, while in the second the nodes were photographs of mechanical components and the arcs were ducts (providing an implicit metaphor of flow between the components).

In this experiment there were two further versions of the editor, designed to have no apparent relationship to the devices being explained. The first of these depicted the four different node types as vegetables. The arcs were shown as lines of spring onions arranged between the vegetables. An example of the resulting diagram is shown in figure 5.11.

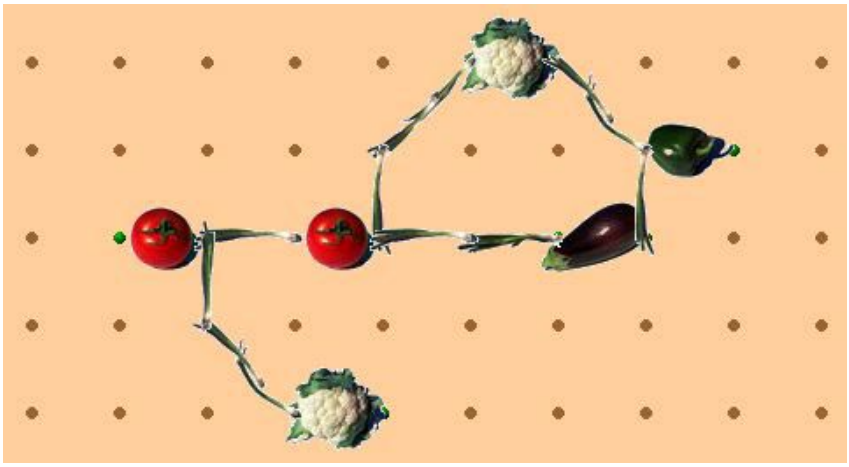


Figure 5.11. Diagram editor based on vegetables

The second new version of the editor depicted the four node types as farmyard animals, and the arcs between them as lines of paw-prints, as shown in figure 5.12.

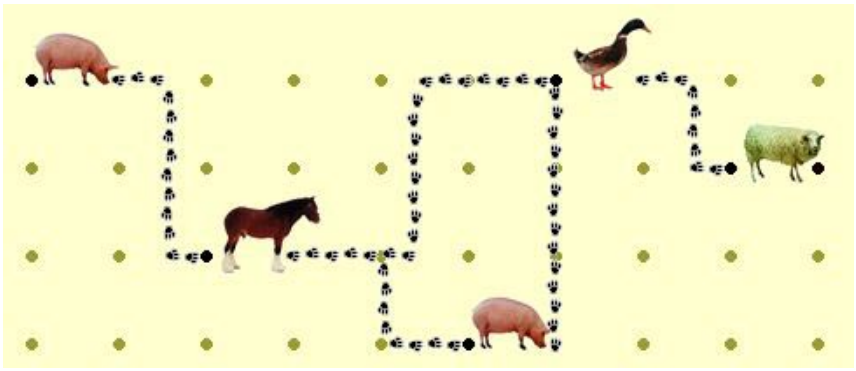


Figure 5.12. Diagram editor based on farmyard animals

The animal editor includes an implicit metaphor of travel between nodes, while there is no such metaphor in the vegetable editor. The metaphor implicit in the animal tracks is more obvious than it is in the mechanical editor, while there is no implicit motion in the vegetable editor. The geometric and mechanical versions of the editor described in experiment 3 were also included as alternatives in this experiment.

Tasks

As in experiment 3, this experiment compared devices incorporating abstract processes to those incorporating concrete processes. Eight new devices were used, however, and there was a second axis of variation: in the complexity of the device to be explained. The eight devices are listed in table 5.2.

Complexity level	Concrete	Abstract
1	pencil sharpener	electric light
2	construction crane	transistor radio
3	central heating system	bank account
4	baked bean factory	British Parliamentary system

Table 5.2. Second set of abstract/concrete devices

The second and third levels of complexity in these devices were intended to correspond to the range of devices in experiments 3 and 4, while the first level was substantially more simple, and the fourth level as complex as possible while being familiar to a lay person.

Equipment

The equipment used in this experiment was identical to that in experiment 3: digitised photographs of the node and arc types, edited with Photoshop, and animated in Director. The secondary tasks used in experiment 3 were removed from the program for this experiment.

Hypotheses

1. That the explicit manipulation of task complexity should result in increased elaboration of the diagrams that are produced.

2. To measure any effect of abstraction and editor size by comparison to the effect of task complexity.

Participants and design

Sixteen participants were recruited from the APU volunteer panel. There were no between subjects factors, and three factors varied within subjects. The first independent variable was the type of device being explained. As in experiment 3, half of the devices involved *abstract* processes, and half involved physical *concrete* processes. There were eight devices altogether, and the second independent variable was the ordinal degree of *complexity* of the device to be explained – there were four levels of complexity for both the abstract and concrete processes. The third independent variable was the type of diagram used for each task – either *animal*, *vegetable*, *mechanical* or *geometric*. The allocation of diagram type to complexity and device type was balanced across subjects, producing a balanced confound design as in experiment 4.

A single measure of performance was recorded. As in experiments 3 and 4, this was the degree of *elaboration* of the diagram, measured in terms of the number of nodes. This measure was used to test both hypotheses.

Procedure

The procedure used in this experiment was very similar to that of experiment 3. It included an animated explanation of the editor operation, followed by a practice exercise, and then eight device explanation tasks. In this experiment, however, the animated explanation demonstrated the geometric editor to all participants. Participants were then shown each of the four editor variants and given an opportunity to experiment with them, in order to confirm that they all worked in the same way, before starting work on the practice exercise. Unlike

experiment 3, there was no planning period (or secondary task) between the allocation of the device to be explained, and the use of the diagram editor.

The eight devices that were explained by participants were designed to incorporate a large range of variation in complexity. They included two extremely simple devices: a pencil sharpener (concrete) and an electric light (abstract). Two corresponded to the least complex devices in experiments 3 and 4: a construction crane (concrete) and a transistor radio (abstract). Two were more complex: a central heating system (concrete) and a bank account (abstract). Two were as complex as possible while being familiar to a layman: a baked bean factory (concrete), and the British Parliamentary system (abstract).

Results

As in experiment 4, the balanced confound design of four levels of complexity with four editor types across only eight tasks did not allow a repeated measures analysis of variance including both factors. Instead, I directly compared effect sizes for the factors of complexity and editor type in a single analysis of all trials. The effect of complexity on elaboration of the diagrams was highly significant, even with this loss of statistical power, $F(3,96)=12.67$, $p<.001$. The effect of the editor type and of abstract versus concrete devices was very small in comparison, as shown in Figure 5.13. Neither the effect of editor nor device type reached statistical significance, $F(3,96)=1.21$, $p=.31$ and $F(1,96)=0.02$, $p=.90$ respectively.

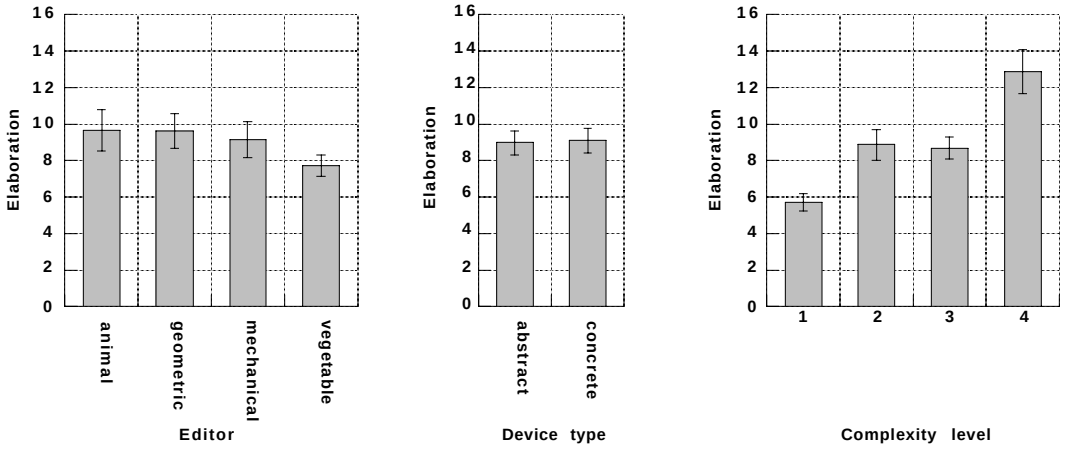


Figure 5.13. Relative effect sizes of complexity, editor, and device type

In order to check for any interaction between the editor being used and the device being explained, I normalised the level of elaboration, relative to all descriptions that were constructed of that device. On this normalised scale, the number of nodes in the most

elaborate description of that device was assigned a value of 100, and the number of nodes in the least elaborate description was assigned a value of zero. I then calculated the normalised elaboration of each diagram linearly along this scale. Figure 5.14 shows the relative elaboration for each task/editor combination. As any participant only used one of the four editors for each device, each point on the graph represents one quarter of the total times that device was described, N=4. There are certain editors which seem to produce more favourable results for particular tasks. Farmyard animals can productively be used to describe the British Parliamentary system, for example. These interactions are not statistically significant over such a small number of trials, unfortunately.

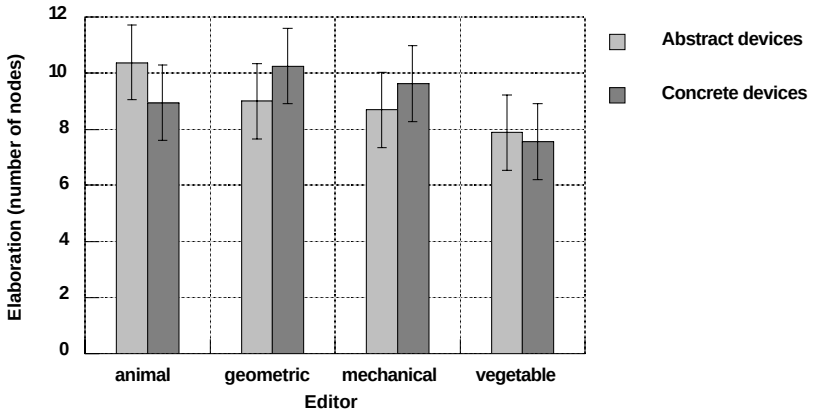


Figure 5.14. Interaction of editor with device type

The normalised scale was used to compare the relative elaboration produced using each editor in the abstract and concrete device sets. There was no significant difference between the editors over all devices, $F(3,45)=1.12$, $p=.352$, and no interaction between the abstract/concrete device manipulation and the elaboration produced with any given editor, $F(3,45)=0.83$, $p=.482$.

Discussion

This experiment was unlike experiment 3, in that each participant used a range of different notations. Every participant experimented with all four editors before the experiment started, and was therefore quite familiar with the distinction between the behaviour of the editor (which was the same in all four cases) and the appearance of the nodes and arcs (different in all four cases). This presentation made the distinction between the syntactic conventions and the arbitrary symbols quite obvious. The instructions given to participants in experiment 3 did imply that they were to treat the symbols as arbitrary, by repeating that the diagram did

not have to "look like anything". Nevertheless, the experience of using several different symbol sets for the same purpose makes the arbitrary assignment of symbols far more explicit.

The results of this experiment show practically no variation in the elaboration of abstract and concrete device descriptions using different symbol sets. It seems likely that this results from participants consistently treating the symbols as arbitrary decorations of otherwise abstract networks. Sometimes those decorations are entertaining (in the case of the farmyard animals), and hence encourage extra productivity, but I do not believe that those cases reflect any underlying difference in the way that the participant has conceptualised the diagram. Even the geometric shapes may be seen as simply another decoration. As Liu and Kennedy (1994) have observed in recall experiments, even simple geometric shapes such as squares and circles can be interpreted as having metaphorical associations with associated mnemonic benefits for recall of congruent associations. More complex geometric figures have also been found to have uniform semantic associations in different cultures (Pickford 1979, Takahashi 1998), explained by Werner and Kaplan (1963) as "concrete-affective" associations.

Experimental work with children has also shown that they are prepared to regard symbols they know to be meaningful as being arbitrary for the purposes of play. This "pre-object" use of symbols has been observed in children using computer drawing packages (Labbo 1996). It has in fact been shown to impede the discovery of representational relationships between the real world and a physical symbol domain, when children are allowed to play with a model of a room in which a toy has been hidden (DeLoache & Marzolf 1992). These observations lend support to the hypothesis that participants in the present experiment treated the symbols in a more arbitrary way as a result of "playing" with each of the editors during the preparation phase of the experiment.

Experiment 6: Other factors affecting diagram planning

In the discussion of the previous experiment, I have suggested that interaction between abstract/concrete devices and different symbol types depends on novelty of the symbols. If this is the case, there were no differences in diagram elaboration in that experiment because participants had become familiar with the notational differences and therefore treated them as more arbitrary.

There are several other potential reasons why the interaction found in experiment 3 was not replicated, however. Firstly, the assignment of devices to the "abstract" and "concrete"

categories was made on a purely intuitive basis. This approach has been typical of previous experimental work comparing abstract and concrete categories (e.g. D'Esposito et. al. 1997), but the distinction may be more subtle than the experimenter assumes. Experiment 6A tests this categorisation on the basis of reports from 20 independent raters.

Secondly, the planning time provided in experiment 3 may have contributed to the difference observed between abstract and concrete devices. Experiment 5 did not allow any planning time, based on the observation that secondary tasks had not affected diagram production. Participants in experiment 3 may however have found it easier to plan abstract devices in the geometric condition, perhaps using verbal strategies. Experiment 6B tests the effect of planning, in an experiment that is otherwise intended to replicate the results of experiment 3 with a different set of devices.

A third possibility is that the experimental situation included a substantial degree of implicit experimental demand. Participants had a fixed amount of time in which to produce their diagram, and they were working in an unfamiliar environment where the addition of each node may have seemed laborious. Experiment 4 has already demonstrated that the environment itself did not unduly constrain diagram elaboration, but experiment 4 tried to reproduce the other conditions of experiment 3, including a fixed time limit for diagram production. Experiment 6C tests the effect of experimental demand by manipulating the time that participants expect to spend on each diagram.

Experiment 6A: Verify abstract/concrete classification

This experiment used the assessments of independent raters to test the earlier assumptions regarding assignment of devices into abstract and concrete categories.

Tasks

Participants in this experiment simply assigned an abstract/concrete rating to each of the devices used in the previous experiments. The devices that were rated were all 15 devices that had been used in experiment 3 and experiment 5 (including the practice example; a toaster).

Equipment

The experimental material consisted of a single page questionnaire. It listed fifteen devices, with a line across the page underneath each one (the questionnaire is reproduced in appendix B.6). The devices were randomly ordered on the page. Each line had a marker at both ends,

with the words ‘abstract’ and ‘concrete’ marked at opposite ends. Participants made a mark on each line to reflect their judgement of abstractness or concreteness for each device.

Hypothesis

> That those devices defined as being abstract in previous experiments would be rated as more abstract.

Participants and design

Twenty participants were recruited from students registered for postgraduate degrees at Darwin College, Cambridge. All participants completed the same single page questionnaire. The only independent variable was the distinction between the 15 different devices, each of which had been assigned in previous experiments to *abstract* or *concrete* categories.

The questionnaire used a single measurement technique. The abstract/concrete judgement was treated as a semantic differential scale – a continuous line which participants could mark at any position. The dependent variable was the position of the mark. The hypothesis was tested by comparing whether those devices defined as being abstract were placed toward the abstract end of the scale, relative to the overall mean.

Procedure

The questionnaire was distributed to students who were waiting for a meeting to begin. The introduction to the questionnaire described the difference between concrete devices (those that involve moving parts or physical processes) and abstract devices (those that do not). Instructions to the participant asked them to make a mark on each line to reflect their judgement of abstractness or concreteness for each device.

Results

The hypothesis was that those devices defined earlier as being “abstract” would all be placed toward the abstract end of the scale, relative to the overall mean. The scale was 150 mm long. With the abstract end of the scale defined as 0, and the concrete end as 150, the mean point of all marks made by participants was toward the concrete end, at 94 mm. All “abstract” devices from the earlier experiments had mean positions closer to the abstract end of the scale than this, and all of the “concrete” devices had mean positions closer to the concrete end. The

toaster, which was chosen as a practice exercise on the basis that it was not too abstract or too concrete, had a mean position of 108 mm: closer to the concrete end than the abstract.

I also compared the relative rankings of the two sets of devices used in earlier experiments. The devices introduced later, in experiment 5, generally received more extreme ratings than those used in experiment 3. Three of the four abstract devices in experiment 5 fell into the first quartile. Only the least complex, the electric lamp, had a more ambiguous position in the second quartile. All four of the concrete devices in experiment 5 fell into the fourth quartile.

Experiment 6B: Planning effect, replicate abstraction effect

This experiment explicitly tested the effect of planning on diagram production, and is also intended to replicate the abstraction effects found in experiment 3 with a different set of devices.

Notation

This experiment used only the two diagram editors based on geometric shapes and mechanical components that had been used in experiment 3, rather than the more fanciful animal and vegetable editors introduced in experiment 5.

Tasks

Participants in this experiment drew diagrams to explain six different devices. These were the six devices that had been found to be either abstract or concrete with the least ambiguity in experiment 6A, as shown in table 5.3.

Complexity level	Concrete	Abstract
2	construction crane	transistor radio
3	central heating system	bank account
4	baked bean factory	British Parliamentary system

Table 5.3. Third set of abstract/concrete devices

Equipment

The equipment used in this experiment was identical to that in experiment 3 and 5: digitised photographs of the node and arc types, edited with Photoshop, and animated in Director. Although a planning period was included, this consisted of a blank screen with a fixation cross in the centre – the spatial tracking and visual noise tasks of experiment 3 were removed from the program.

Hypotheses

1. That the effect of device complexity on elaboration would be observed again.

2. That the interaction of device abstraction and editor type observed in experiment 3 would reappear.

3. That the provision of planning time would increase speed of production, even for participants who plan using verbal rehearsal, as proposed in experiment 3.

Participants and design

Sixteen participants were recruited from the APU volunteer panel. I varied two between-subjects factors, and two within subjects factors. The first independent variable returned to the between-subjects allocation of editors as used in experiment 3; each participant used only the editor based on *mechanical* nodes and arcs or on *geometric* nodes. The second between-subjects factor was whether or not participants were given time to *plan* their diagram after learning what it was. Half of the participants were given one minute planning time before starting each diagram, while the other half were given none. The between-subjects factors were balanced across all participants.

There were also two independent variables designed as within-subjects factors. The participants explained six devices; these were classified as either *abstract* or *concrete*, and they included three different levels of *complexity*.

Two dependent variables were measured – the degree of *elaboration*, measured as the number of nodes in the diagram, and the *speed* of production, measured as the average time interval between creation of the first ten elements. The first two experimental hypotheses were tested in terms of the effects of device complexity, device abstraction and editor type on elaboration. The third was tested in terms of the effect of planning time on speed of production.

Procedure

The procedure used in this experiment was almost identical to that of experiment 3, except that participants in the planning condition were not required to carry out a secondary task while planning their diagrams. Participants watched an animated explanation of the editor operation, drew a practice diagram, and then drew diagrams to explain six different devices. Presentation order was balanced as for experiment 5.

Results

The first hypothesis was that the previously observed effect of device complexity on diagram elaboration would again be found. This was in fact observed. The mean elaboration of the six devices is shown in figure 5.15. In testing this first hypothesis, there was a significant main effect of complexity on elaboration , $F(2,24)=4.92$, $p<.05$. As before, the abstract and concrete devices at each level of complexity did not result in significantly different levels of elaboration, $F(1,12)=1.00$, $p=.338$, and there was no interaction between complexity and abstraction, $F(2,24)=0.09$, $p=.916$.

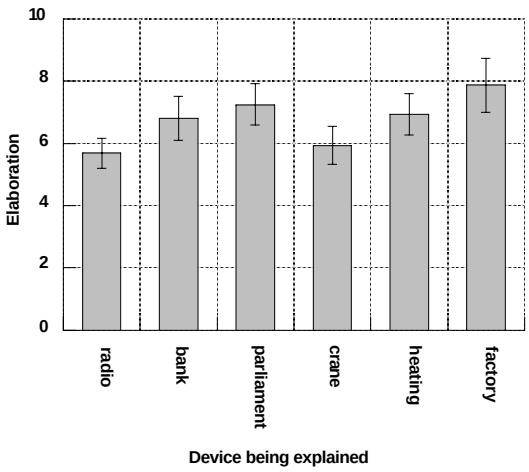


Figure 5.15. Mean elaboration of diagrams explaining six devices

The second hypothesis was that the interaction between device abstraction and the use of mechanical or geometric editors observed in experiment 3 would be replicated in this experiment. The results from this experiment did not replicate that finding. As before, there was no main effect of editor type, $F(1,12)=0.51$, $p=.489$. In this experiment, however, neither was there any significant interaction between device abstraction and the editor type, $F(1,12)=1.56$, $p=.236$.

The third hypothesis was that providing planning time would increase speed of production in the early part of diagram creation. There was a significant effect of the planning variable on speed, $F(1,12)=7.52$, $p<.05$, but this effect was in the opposite direction to that predicted. Participants who were given planning time drew their diagrams more slowly than those who had no planning time. There is an interaction between planning time and device complexity that may help to explain this. As shown in figure 5.16, devices at different levels of complexity are explained with similar degrees of elaboration when no planning time is provided. When participants were given a minute to plan the diagram, they apparently produced diagrams that were elaborated in proportion to the complexity of the device being explained. For the simplest devices, there was a tendency for participants to produce less complex diagrams when they were given time to plan the diagram than when they were not given planning time. This interaction was only marginally significant, however, $F(2,24)=4.92$, $p=.065$.

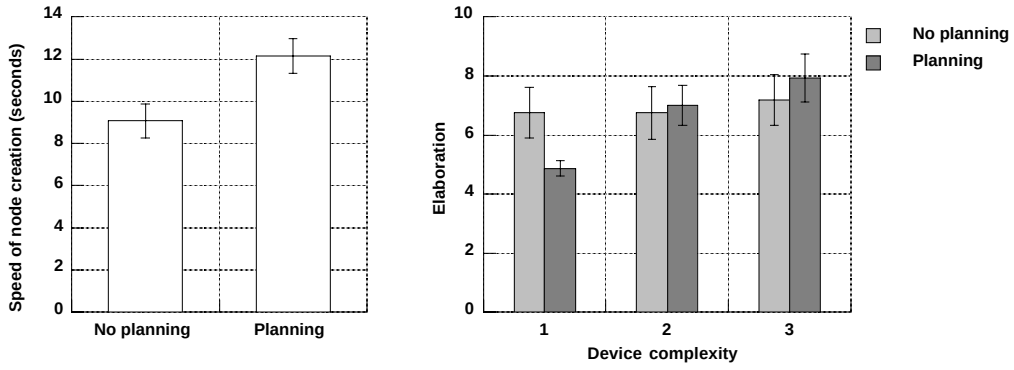


Figure 5.16. Effect of planning time on diagram elaboration and production speed

Experiment 6C: Experimental demand

This experiment tested the effect of experimental demand by manipulating the time that participants expected to spend on each diagram. These results have previously been reported in Blackwell (1997a).

Notation

In this experiment participants drew diagrams by hand, as in experiment 4. The instructions given to participants about the form of diagrams were identical to those in experiment 4.

Tasks

This experiment returned to the complete set of eight devices first introduced in experiment 5. Device abstraction was not considered as a factor in this experiment, so the two simplest devices, although found to be ambiguous regarding abstract/concrete judgments in experiment 6A, were included to give a wider range of complexity.

Equipment

Participants in this experiment used pencil and paper, as in experiment 4.

Hypotheses

1. That the variation in device complexity should result in the same variation in elaboration observed in experiment 6B, despite the fact that diagrams were being drawn on paper rather than with a special editor.

2. That the effect of experimental demand might be sufficiently large by comparison to the effect of device complexity to explain the variations associated with the planning factor in experiment 6B.

Participants and design

Eight participants were recruited from the APU volunteer panel. There were no between subjects factors, and two within-subjects factors. The first independent variable was the degree of *complexity* of the devices to be explained, as in experiment 5. Device abstraction was not considered as a factor in this experiment. The second independent variable was an implicit manipulation of experimental demand. While drawing four of the diagrams, participants used a stopwatch to monitor the length of time that they spent drawing, providing an implicit concern with *speed* of drawing. When drawing the other four, subjects were explicitly told that time was not important, and they should make the diagrams as *detailed* as possible.

There was a single dependent variable – the degree of *elaboration*, in terms of the number of nodes in the diagram. The two hypotheses were tested with respect to this variable.

Procedure

The procedure for this experiment was similar to that of experiment 4, in which diagrams were drawn in a booklet containing A3 sheets of paper. The booklet first described the required form of diagram, using the same text that was used in experiment 4. Participants then completed a practice exercise, explaining the internal workings of a toaster.

Participants then drew four diagrams in the *speed* condition. The booklet asked them to start a stopwatch, draw the first four diagrams, and then write down the time that they had spent drawing. After this, the booklet instructed them to stop the stopwatch and put it away, then spend as much time as they liked drawing four more diagrams, which were to be made as *detailed* as possible. The presentation order of the eight devices, and allocation of devices to the speed/detailed conditions were balanced across all participants.

Results

The first hypothesis was that the variation in device complexity should result in the same variation in elaboration observed in experiment 6B, despite the fact that diagrams were being drawn on paper rather than with a special editor. As shown in figure 5.17 there was a significant variation of diagram elaboration, in the direction expected with increasing device complexity, $F(3,21)=6.57$, $p<.01$.

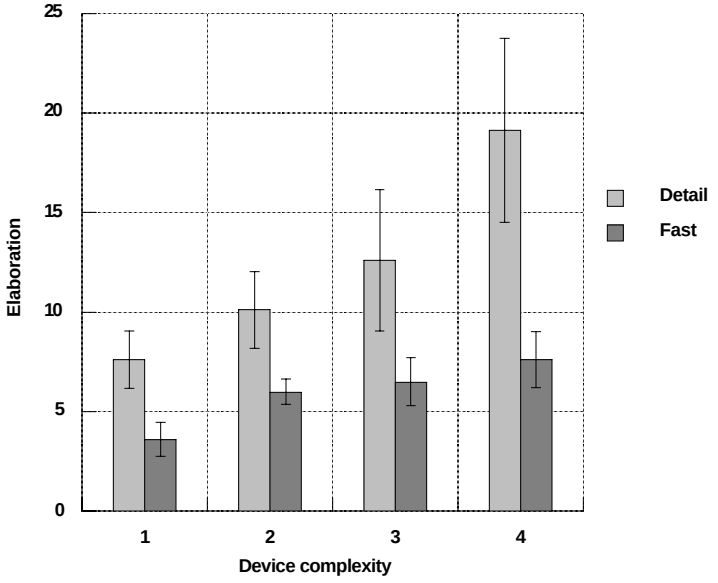


Figure 5.17. Variation in elaboration with device complexity and experimental demand

The second hypothesis was that the effect of experimental demand might be comparable to the effect of device complexity. As can be seen in figure 5.17, the difference in elaboration between the two demand conditions is significant, $F(1,7)=13.06$, $p<.01$. There is also, however, a large interaction effect between complexity and demand condition. When participants are working with an implicit time constraint, there is relatively little variation between the elaboration of the least complex and most complex descriptions. When asked to make their diagrams more detailed, participants were able to produce far more elaborate diagrams for the more complex devices. This interaction is only marginally significant, however: $F(3,21)=2.97$, $p=.055$.

Discussion

These three experiments investigated several areas of uncertainty arising from experiment 3, 4 and 5. Firstly, the categorisation of devices into those involving abstract and concrete processes appears to have been quite straightforward. The discovery that the second set of devices (first introduced in experiment 5) were more strongly differentiated than the original set also encouraged the attempt to replicate the original interaction with a different set of devices.

Experiment 6B failed to replicate the result of experiment 3, however. There was no evidence at all in support of the previously observed interaction. This suggests that the interaction observed in experiment 3, if it were to be verified as robust, probably resulted from the specific set of devices used in that experiment. In fact, a single device contributed most of the interaction effect. The pocket calculator was explained to a far greater level of elaboration when geometric symbols were being used; an average of 13.0 nodes, compared to 7.8 nodes in the pictorial condition. This was the largest difference in means for any device, but the interaction over all devices was only marginally significant, $F(5,110)=2.24$, $p=.055$. On inspection of the diagrams produced in that experiment, it seems there is a straightforward explanation why the calculator should be a special case. Geometric symbols are readily used to express mathematical operations, so the diagrams produced often included several elements representing each arithmetic operation. The pictorial nodes were used to represent processing, but were less likely to represent individual mathematical operations.

The most surprising result in experiment 6B was that participants drew less complex diagrams when they were given time to plan in advance. This effect appeared to be restricted to the least complex devices, however. It suggests that participants who drew diagrams "on the fly" simply elaborated them until they looked sufficiently complex, rather than thinking in advance about the level of elaboration that was justified. This proposal suggests that the

observed effect is due to experimental demand rather than any performance deficit associated with planning. Experiment 6B also confirmed an unusual observation made in experiment 3. In experiment 3, those participants who reported no difficulty with planning actually produced their diagrams more quickly when they were given a secondary task. A similar effect is observed here – when participants were given no planning time, they produced their diagrams more quickly. This suggests that speed of production is not a good measure of whether a diagram has been planned in advance. In this case, lack of planning also resulted in greater consistency between tasks – perhaps because participants resorted to a standard schema rather than planning a more original diagram.

All of the experiments described in this chapter have involved participants describing the operation of some device under time constraints. Furthermore, none of the experiments included any explicit instructions on the level of elaboration that participants were expected to produce. The level of elaboration that they did produce was therefore influenced not only by their knowledge of the device, by their planning strategies and by the tools that they were given, but by the implicit requirements of the experimental context – they were unlikely to expend much more effort on each diagram than they believed was required of them. This factor is likely to have affected all tasks equally, but may have had the effect of reducing the range of elaboration produced. As a result, the manipulations of editor and task characteristics in these experiments may have had larger effects in other circumstances. Despite this caution, if there was an effect of pictorial metaphor or task abstraction in the experiments reported in this chapter, it was too small to be observed. It was certainly far smaller than either the effects of device complexity or experimental demand as observed in Experiment 6C.

Chapter 6: Metaphor for Mnemonic Diagrams

The advantages proposed by this mode of representation are to facilitate the attainment of information, and aid the memory in retaining it: which two points form the principal business in what we call learning.

The Statistical Breviary,
W. Playfair, 1801, p. 14.

Chapters 4 and 5 have described investigations of two widely held theories of diagram use: that novices can use diagrams as physical metaphors of abstraction to gain expertise, and that diagrams accommodate the use of mental images in problem solving. Neither series of experiments found convincing evidence for the expected strategies, but this does not necessarily mean that the claimed advantage of metaphorical diagrams, as reviewed in chapters 1 and 2, is completely unjustified. Even if metaphors simply provide a mnemonic aid when learning to use a diagram, this could result in substantial improvements in task performance. This could explain the results found in experiment 2, where a nonsensical metaphor may simply have prompted bizarre (but effective) mnemonics.

In experiment 1, I tested for differences in memorability between metaphorical and non-metaphorical diagrams. Of the four novices who used the non-metaphorical version, two of them asked far more often for reminders about component functions. The fact that this effect was only observed for half of an already small experimental group made firm conclusions impossible, but it supports the possibility that metaphors support mnemonic performance rather than problem solving.

The literature certainly includes numerous claims (besides those reviewed in survey 1) that metaphor makes representation systems easy to learn. Payne (1988) describes improved memory for abbreviated command languages when they have a metaphorical explanation, while Simpson and Pellegrino (1993) describe small (10%) improvements in recall when novices use a visual representation involving a geographical metaphor. Where memory for visual representations is concerned, however, it may be the case that any systematic interpretation will improve memory. Bower, Karlin and Dueck (1975) found that reproduction of abstract visual riddles was far more accurate when participants were given a meaningful interpretation of the picture. Liu and Kennedy (1994) found that verbal recall was improved when the words were inscribed within simple geometrical symbols having stereotypical interpretations congruent with the words. Bartlett (1932) also proposed that memory for abstract shapes would be improved by seeing them as real objects.

Experiment 7: Comparison of good / bad / no metaphor

In experiment 2, participants carried out a combination of problem-solving and mnemonic tasks, using four diagrams composed of abstract shapes. The meaning of each diagram was described either with the addition of a systematic metaphor, or with a nonsensical metaphor. The quality of the metaphor given appeared to make little difference in performance to novice diagram users. This result can be seen as supporting the occasional critiques of metaphor use in HCI. Kieras and Bovair claimed that understanding of complex devices would not be improved by a metaphor or analogy because it is "unlikely to support precise inferences" about specific actions that the user should make (Kieras & Bovair 1984, p. 272). Furthermore, Kieras and Bovair warned that the metaphor might be poorly designed, or that novices may draw invalid conclusions from it, in which case it would impair performance by comparison to more precise instructions. This might certainly have been expected with the nonsense metaphors of experiment 2.

This experiment further explores the result of experiment 2, by introducing a third condition with no metaphor at all. It also modifies the tasks that were used to evaluate diagram understanding in experiment 2. In that experiment, one of the tasks involved completing a diagram by drawing missing graphical elements. The drawing task was least affected by the use of metaphor. It seems possible that some participants treated it as a simple figure reconstruction task, perhaps as a result of having carried out visually similar tasks (such as the Rey-Osterrieth complex figure recall test) in previous experiments encountered during their membership of the APU volunteer panel. If the drawing task had encouraged participants to rely on image-based memory strategies, rather than using the metaphor to interpret the diagram, this might have resulted in a modality-specific interference effect, similar to the finding by De Beni, Moé and Cornoldi (1997) that using the mnemonic method of loci interferes with recall of written texts, but not oral presentations of the same text. Interference of this type might also suggest dual-coding effects (Paivio 1971) governing the mnemonic benefit of the symbols. This is explored further in experiment 9. In the current experiment, the diagram drawing task used in experiment 2 was simply removed.

Notation

This experiment used novel diagrams: the four that had been used in experiment 2, and two further diagrams that, as in experiment 2, expressed computational concepts in familiar situations. As for the original four diagrams, the explanation of each diagram could incorporate either a *systematic* metaphor that compared the graphical elements to some

physical situation with an appropriate structure, or a *nonsense* metaphor that compared them to an irrelevant physical situation. The original four diagrams expressed the following concepts:

- closure (a set of values that is defined for use in a specific context);
- database join (combining tables of data on the basis of common values in each table);
- flow of control (sequences of execution states such as repetition and choice); and
- visibility (hiding working material within a function to simplify its interface).

The two new diagrams were designed to be at the less difficult extreme of those used earlier. They expressed the concepts of:

- remote execution (defining an algorithm that can spread across several computers); and
- selection (choosing the next state of the program based on some logical criterion).

The diagram expressing remote execution is shown in Figure 6.1. The task context described a car manufacturing operation, where the manufacture of some parts or sub-assemblies might be subcontracted to other factories. The diagram shows each sub-assembly as a box that can contain other sub-assemblies (a recursive definition). A rectangle without decoration indicates that the assembly will take place in the same location as for the containing box. A rectangle with a "V" marked across the top indicates that the assembly will take place in a different location.

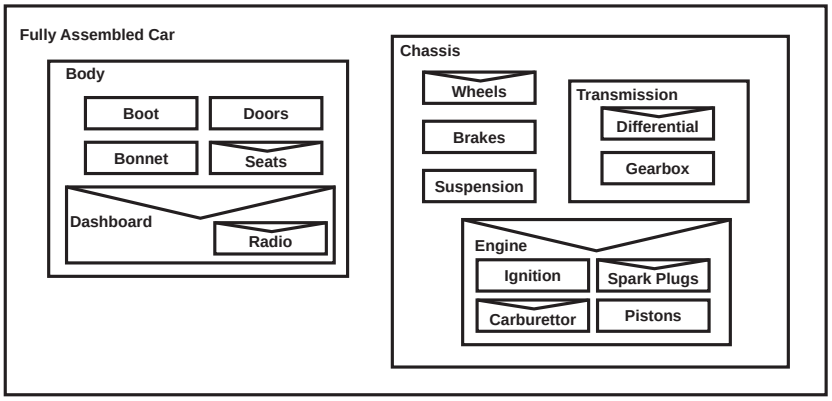


Figure 6.1. Diagram showing remote execution in terms of car manufacture.
Eg: Seats are made in a different factory from the body, but the bonnet is made in the same factory

For this diagram, the systematic metaphor described the plain rectangles as sheets of paper which could be used to instruct the factory workers about assembly operations. The rectangle with the "V" at the top was described as resembling an envelope in which instructions would have to be posted to a different factory if the assembly was being done elsewhere. The

nonsense metaphor described the boxes as toolboxes, with the "V" being an open drawer allowing you to see what is inside the box.

The diagram expressing selection is shown in Figure 6.2. The task context described a decision in planning a dinner menu: the decision of whether or not to eat salad depends on the weather, and on whether some combination of appropriate ingredients are available in the garden, at shops or in the refrigerator. The diagram shows contributing factors linked by lines, where several lines can be combined conjunctively (shown as a series of links) or disjunctively (shown as a twisted rod).

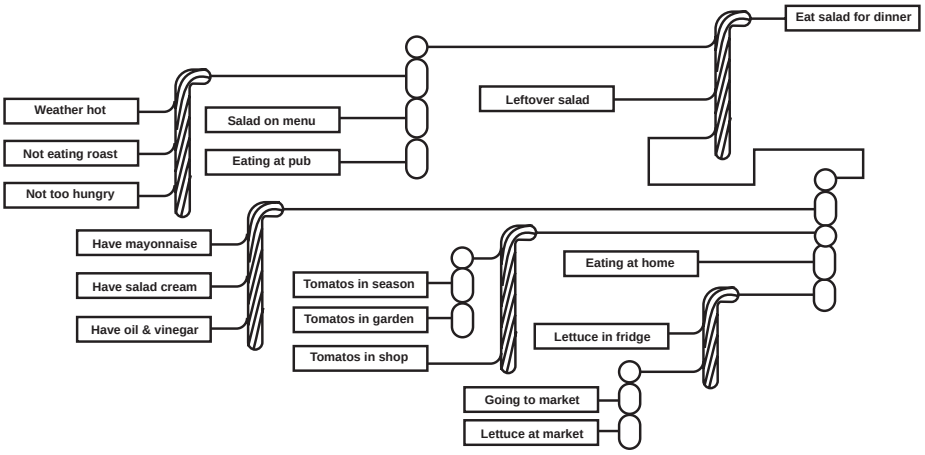


Figure 6.2. Diagram showing selection in terms of menu planning.
Eg: leftover salad or *some other combination results in eating salad for dinner*

For this diagram, the systematic metaphor described the diagram as a system of strings being pulled. The conjunction symbol resembled a chain – if one link in the chain breaks, it will not pull the string attached to its end. The disjunction symbol resembled a rope – any number of strands can break, but so long as one remains, it will pull the string attached to its end. The nonsense metaphor described the disjunction symbol as resembling a furled umbrella, and the conjunction symbol as resembling a string of sausages.

Tasks

As in experiment 2, participants answered comprehension questions for examples of each diagram. These questions were phrased to involve an element of problem solving using the notation, rather than simply providing definitions of diagram elements, or reading information directly from the diagram.

In a second task, participants completed incomplete diagrams by writing in missing labels. A list of the missing labels was provided, along with some problem-domain constraints stating where those labels could be placed.

Experiment 2 had also included a test in which incomplete diagrams were completed by drawing, but that task was omitted from this experiment, for reasons explained in the introduction. This also reduced the number of tasks using each diagram from three to two, thereby providing sufficient time in the experimental session to learn six diagrams rather than four as in experiment 2.

Equipment

As in experiment 2, material was presented to participants in booklet form. Participants wrote directly in the booklet, and used a stopwatch to record the amount of time they spent working on each page. Pages from the booklet are reproduced in appendix B.7.

Hypothesis

> That performance when no metaphor was provided would be intermediate between the systematic metaphor and nonsense metaphor cases.

Participants and design

Twelve participants were recruited from the APU volunteer panel. There were no factors varied between subjects, and two factors within subjects. The first independent variable had three values in this case: diagrams were presented to participants with either the *systematic* metaphor, the *nonsense* metaphor, or *no metaphor* at all. As in experiment 2, the design was a balanced confound, with the allocation of metaphor condition to each of the six diagrams balanced across subjects. The second independent variable was the form of task: *comprehension* questions or *completion* of incomplete diagrams.

As in experiment 2, two dependent variables were used to measure performance: the *speed* with which participants completed comprehension and completion tasks, and *accuracy* in those tasks. Accuracy scores were again normalised for each task, so that treatment effects could be compared using scores on different tasks. The first hypothesis regarding performance was tested in terms of both shorter task completion times and higher normalised scores.

Procedure

Participants in this experiment worked through a booklet, as in experiment 2. The first page instructed them to work through the booklet in order, and to write at the top of each page the time that they started work on that page.

The main part of the booklet contained 18 pages: three pages for each of the six diagrams. In each group of three pages, the first page explained the diagram with the appropriate metaphor condition, the second page asked comprehension questions, and the third page asked the participant to complete a diagram by adding text.

The assignment of metaphor condition to each diagram was balanced across participants, as was the presentation order of metaphor condition. The six diagrams were always presented in the same order for all participants, with the least difficult (those that had resulted in the best performance in experiment 2) presented first in order to increase the confidence of participants at the start of the experimental session.

Completed booklets were scored by comparison to ideal worked solutions, and marking was done while blind to the metaphor condition with which diagrams had been explained. Comprehension questions were scored by awarding one mark for each piece of information that was in accordance with the worked solution, and subtracting one mark for any additional pieces of information given, if it was inconsistent with either the problem constraints or the definition of the diagram. Diagram completion tasks were scored by awarding one mark for each label that was in the same place as the worked solution, and subtracting one mark for each label in a place that was inconsistent with the problem constraints or the diagram definition.

Results

The hypothesis for this experiment was that performance with no metaphor would be intermediate between that in the systematic metaphor and nonsense metaphor cases. In fact, there was no significant difference in speed between the three cases, $F(2,22)=0.31$, $p=.735$. Furthermore, the mean accuracy in the no-metaphor case was actually slightly higher overall than in either of the other cases, as shown in table 6.1. This difference in accuracy was not significant either, however, $F(2,126)=0.37$, $p=.694$.

Metaphor type	Combined mean score
Nonsense	46.2
None	51.8
Systematic	47.4

Table 6.1. Mean scores in experiment 7 metaphor conditions

Why might the absence of a metaphor improve performance? Participants might have noticed that the non-metaphorical explanations were shorter than the others in the booklet, and realised that some systematic motivation for the choice of symbols had been hidden from them. They may well have constructed their own explanatory metaphor at this point. A self-generated explanation may even be a superior mnemonic to the metaphor provided in other explanations (as argued in the discussion section below). In order to test this, I compared the time that participants spent reading the diagram explanation. Reading time would normally be shorter in the condition with no metaphor, as the text is shorter. If participants were constructing their own explanations, reading time should be longer for the condition with no metaphor.

Reading times for each metaphor condition are shown in table 6.2. Reading time is in fact shorter for the no-metaphor condition. It is longest for the nonsense condition, suggesting that participants spend more time trying to make sense of the nonsense metaphor. The variances in reading times are very different, however – the variance in reading time is much greater for the metaphor conditions than for the condition with no metaphor. Levene's test for equality of variances confirms that variances in reading times are significantly different: a) when comparing variances of the no-metaphor and systematic metaphor reading time distributions, and also b) when comparing no-metaphor to the nonsense metaphor; $F(1,47)=7.25$, $p<.01$ and $F(1,47)=12.66$, $p<.01$ respectively. This is in accordance with unsolicited comments made by two of the twelve participants, that they stopped reading the second paragraph of the explanations (the paragraph containing the metaphors). Both of these participants had received a nonsense metaphor in the first diagram of the booklet. Presumably these were so unhelpful that these two participants (and possibly others) decided to discard all the metaphors without further evaluation.

Metaphor Type	mean reading time (s)	standard deviation
Nonsense	126.21	13.944
None	95.60	5.631
Systematic	104.92	12.160

Table 6.2. Mean reading times for diagram explanations

Discussion

This experiment repeats the finding of experiment 2, that systematic metaphors are of little assistance in remembering and interpreting these diagrams. Performance with systematic metaphors is once again similar to that with nonsensical metaphors. These two treatments have more in common, in fact, than a case with no metaphor at all.

In analysing these results, I have considered the possibility that participants may be constructing their own metaphor in the case when none is given. This has previously been found to assist novices learning to use computer systems. Carroll and Mack (1985) describe an unpublished study by Carroll and Lasher, in which learning was improved when users created their own metaphor. Jones (1984) has also noted that novices learning a programming language invent their own metaphors to explain the behaviour of their program by comparing it to other types of software that they are familiar with, such as word processors.

There is certainly clear evidence that some participants in this experiment ignored the metaphorical explanations, presumably substituting their own mnemonic strategies. The range of potential strategies is very large, and is subject to individual variation (MacLeod, Hunt & Mathews 1978, Kaufmann 1979, Matsuno 1987, Riding & Douglas 1993, Sein et. al. 1993) as well as cultural variation (Kearins 1981) and differences in self-image (Katz 1983). This possibility is explored in the following two experiments by asking participants to report, after completing the experiment, what mnemonic strategy they had used for each diagram.

Experiment 8: Explicit metaphor as a mnemonic aid

In experiment 7, as in experiment 2, diagram metaphor was assessed in terms of the benefits it would provide in learning to use the diagram for problem-solving tasks. Experiment 7 raised an interesting question regarding the effect of individual mnemonic strategies – some differences in performance appeared to result from mnemonic benefits which may have been mostly obscured by the substantial problem-solving demands in the experimental tasks. A similar distinction between memory and comprehension of diagrammatic material can be found in an experiment by Potter et. al. (1986). Participants were presented with rebus sentences – sentences in which some of the words were replaced by pictures. They then performed both recall tasks and plausibility judgement tasks. Potter et. al. found that plausibility tasks took longer when pictures were included in a sentence, but that recall tasks took the same amount of time. They use these results to argue that semantic judgements

involve lexical representations, and that additional time is required to translate pictorial material into lexical form.

The tasks used in experiments 2 and 7 involved a substantial degree of problem solving. If, as Potter et. al. claim, semantic processing of pictorial material is slower than that of verbal material, interpreting the problem statements in metaphorical terms may actually have impaired performance. This could have some bearing on the slight improvement in performance when no metaphor was given in experiment 7.

In this experiment, the tasks were therefore modified to emphasise recall of the instructional material rather than problem solving. All the diagram explanations were given at the start of the experiment, resulting in an interval of around 20 minutes between presentation and test. An explicit recall test, with no problem-solving component, replaced the comprehension questions. The diagrams themselves were also modified, including two new diagram types which emphasised recall of individual symbols rather than complex geometric syntax. In these simpler diagrams and tasks, any potential handicaps arising from semantic access to pictorial material should be reduced, and the residual mnemonic advantages of instructional metaphor should be clearer. The expected mnemonic advantage can again be explained in terms of the experiment by Bower, Karlin and Dueck (1975) that was described in the introduction to experiment 7 – they found that recall of a visual riddle was improved when a pictorial interpretation was given.

Notation

Participants in this experiment learned to use novel types of diagram, as in experiments 2 and 7. These included two of the diagrams that had been used in those experiments: one presenting flow of control as a washing machine cycle, and one presenting visibility as telephone availability. There were also two new diagrams. These expressed spatial concepts rather than abstract computational concepts, and the spatial organisation of the diagram had a direct correspondence with the spatial layout of the situation that it referred to. The full explanations of these diagrams, as presented to participants, have been reproduced in appendix B.8.

The first of these new diagrams was essentially a map: the two dimensions of the paper were used to show the plan view of a gold mine. The map was schematic rather than pictorial, and it was annotated with symbols indicating what sort of excavation would be required at different locations. An example of the diagram is shown in figure 6.3. The six symbols represent large deposits of gold, individual whole gold nuggets, sprinkled gold powder, rock which must be

crushed to yield gold ore, as well as places where it was necessary to cut through rock walls, or removing blockages from tunnels.

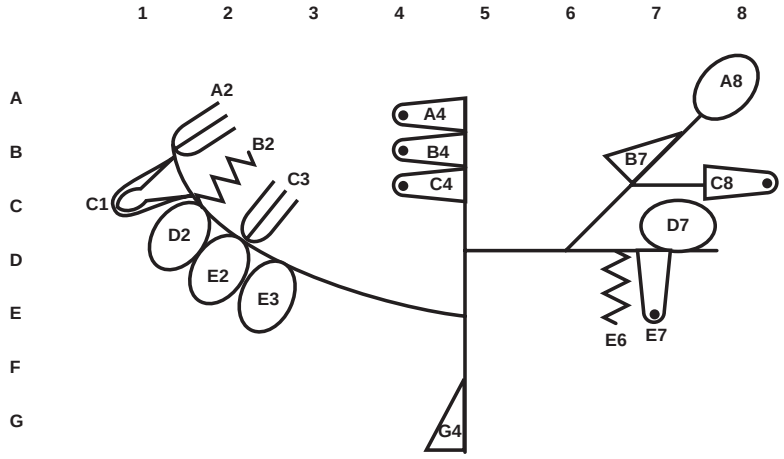


Figure 6.3. Diagram showing gold mine layout

Each of the six symbols could be explained by giving it a metaphorical interpretation. A single metaphor domain was chosen, in which gold mining operations were related to table cutlery. The metaphorical explanation of the diagram compared three of the symbols to a knife, fork and spoon: the knife expressed cutting through rock walls, the fork picking up individual nuggets and the spoon scooping up bulk deposits of gold. The other three symbols were compared to a salt shaker (sprinkling of gold dust), a nut cracker (crushing gold ore) and a corkscrew (removing blockages from tunnels).

The second new diagram used the two dimensions of the paper to represent altitude and time/distance as an aeroplane approaches landing. An example of the diagram is shown in figure 6.4. This schematic diagram also included six symbols to represent actions taken by the pilot: checking for a clear path, lining up with the runway, turning landing lights on, selecting different ranges of engine speeds, slowing down and lowering landing gear.

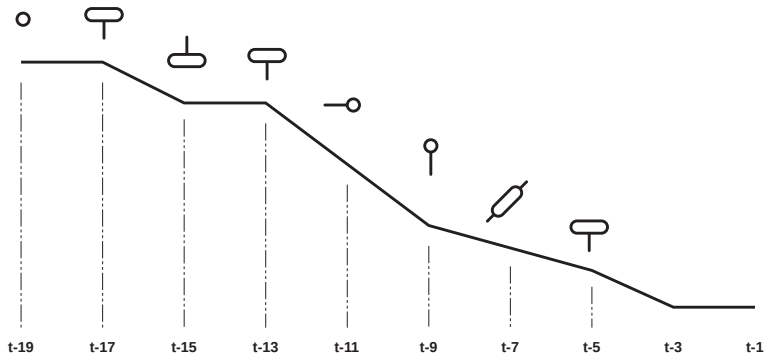


Figure 6.4. Diagram showing aircraft landing approach

The explanatory metaphor for this diagram was created by analogy to the controls of a car. Lining up with the runway was represented by a simple circle like a steering wheel. The symbol for selecting ranges of engine speeds was compared to a gearlever, the symbol for slowing down to a brake pedal, and the symbol for lowering landing gear to a handbrake. The symbol showing when the pilot should check for other planes in the area was compared to a rear vision mirror. Finally, the symbol for turning on landing lights was described as an indicator stalk on the side of a steering column.

The two computational diagrams from experiments 2 and 7 were also modified slightly, so that they also included six different symbols which had to be memorised. I added another symbol to the flow of control diagram to indicate the measurement of some quantity (such as temperature or water level) which might start or stop a process. This symbol was described metaphorically as a gauge. The modified diagram is shown in Figure 6.5.

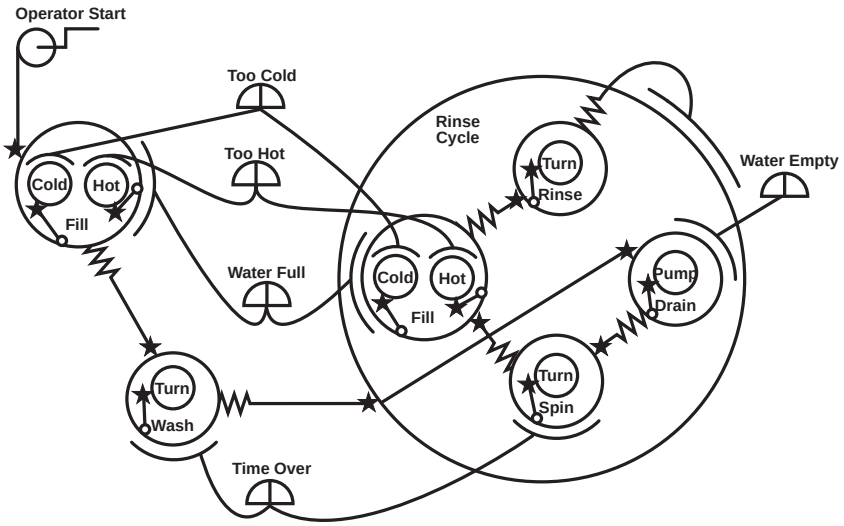


Figure 6.5. Flow of control diagram including six different symbols

The visibility diagram introduced in experiment 2 (and illustrated in appendix B.2.) was used again here. No further symbols were added to it, but the instructions now explicitly described straight lines as a sixth meaningful element (they had previously been treated as default "plain" lines distinguished only because of the fact that they were not dashed). The metaphorical explanations of the two types of dashed line were the same as in experiments 2 and 7. Plain lines were now described as a footpath, along which a postman could walk to deliver messages in writing, as opposed to the higher speed road and rail connections represented by dashed lines.

Tasks

Memory for the diagram definitions was tested using two different tasks. In the first, participants completed a diagram from which all the symbols had been removed, drawing appropriate symbols according to a set of problem constraints phrased in terms of the problem domain. This task tests both comprehension of the diagram definition and memory for symbol form.

In the second task, participants were shown a set of six symbols taken out of the diagram context, and were asked to write the meaning of each symbol alongside it as a straightforward recall test. All tasks are illustrated in appendix B.8.

Equipment

As in experiments 2 and 7, material was presented to participants in booklet form. Participants wrote directly in the booklet, and used a stopwatch to record the amount of time they spent working on each page.

Hypotheses

1. That problem solving performance using the two concrete diagram types (mine layout/cutlery and landing path/car controls) would be superior to that using the abstract diagrams.

2. That provision of a metaphor would improve memory for the symbols used in the diagram, and that this effect would be larger in the case of the abstract diagram types than for the concrete diagrams.

Participants and design

Eight participants were recruited from the APU volunteer panel. There were no factors varied between subjects, and three independent variables within subjects, The first independent variable had two levels: the metaphor was either *present* in the explanation of the diagram, or *absent*. The second independent variable was the nature of the diagram. The two new diagrams both map space in the diagram to a *concrete* physical dimension: to the ground plan of the gold mine, or to altitude along the flight path. The two diagrams expressing computational concepts only use space topologically to represent *abstract* relationships. These two factors form a latin square, but the allocation of metaphor/space conditions to diagrams was balanced across participants, producing the same balanced confound as in experiments 2 and 7. The third independent variable was the type of task used to test memory for the diagram definitions; the *completion* and *recall* tasks described above.

There were three dependent variables: the time taken to *read* the diagram explanation, *speed* in the completion and recall tasks, and *accuracy* for the completion and recall tasks. Accuracy scores were again normalised for each task, so that treatment effects could be compared using scores on different tasks. The two hypotheses were tested in terms of these normalised scores.

Procedure

As in experiments 2 and 7, presentation order was established by order of pages in the booklet. In this experiment all four diagrams were presented together at the beginning of the booklet. These were followed by four diagram completion tasks (in the same order as the diagrams had been explained), and then by the four symbol definition tasks. At the end of the booklet, a page of debriefing questions asked participants to report what technique they had used to remember each set of symbols.

Completed booklets were scored by comparison to ideal worked solutions, and marking was done while blind to the metaphor condition with which diagrams had been explained. Diagram completion tasks were scored by awarding up to three marks for each of the six symbols. One mark was awarded if the form of the symbol was recognised by a rating panel (the organisation of the rating panel is described separately below, under the heading Experiment 8A). A further mark was awarded if the form of the symbol was precisely as in the original explanation (i.e. all elements of the symbol are present and they are oriented correctly to each other). A third mark was awarded if the symbol was included in all the locations where it appeared on the worked solution, and no more.

The symbol definition tasks were scored by awarding up to three marks for the definition of each of the six symbols. One mark was awarded if the definition distinguished the interpretation of this symbol from that of the other five symbols. A second mark was given if the definition was completely accurate. A mark was subtracted if the symbol was given an interpretation that should have been allocated to a different symbol.

Results

One participant in the original group of eight completed the test booklet out of order, after missing the page that provided the initial explanation of one of the diagrams. A ninth participant was recruited to replace those results, and the out-of-order results have not been considered any further.

The first hypothesis was that tasks using the two simpler concrete diagram types would be completed more quickly than those using the abstract diagrams. Task completion times in the different conditions are shown in Figure 6.6. As predicted, participants took twice as long to complete tasks using the abstract diagrams, $F(1,7)=12.20$, $p<.01$. There was no main effect of metaphor presence on mean task completion time, and there was no interaction of metaphor with the time taken to complete either type of diagram or either task.

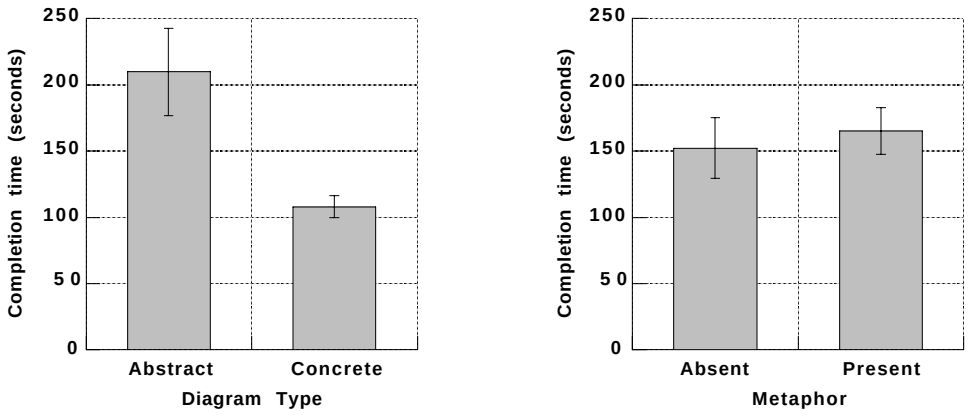


Figure 6.6. Task completion times for each condition in experiment 8

The second hypothesis was that provision of a metaphor would improve memory for the symbols used in the diagram, and that this effect would be larger in the case of the abstract diagram types than for the concrete diagrams. A multivariate comparison of completion time and accuracy (MANOVA) shows a two way interaction between diagram type and recall task performance, $F(2,6)=9.96$, $p<.05$ – in the abstract diagrams, accuracy in the symbol recall task was superior to that in diagram completion tasks. For the concrete diagrams, the reverse was true, as shown in figure 6.7. The inclusion of metaphor was apparently associated with a slight improvement in accuracy for recall tasks, and a slightly greater improvement for diagram completion tasks, but neither the main effect of metaphor nor the interaction is significant, $F(1,7)=0.29$, $p=.605$ and $F(1,7)=0.001$, $p=.978$. There was no improvement at all for abstract diagram types, however. Inclusion of an explanatory metaphor produced improved scores in the concrete diagrams, but actually impaired performance in abstract diagrams, as shown in figure 6.8. This interaction is marginally significant, $F(1,7)=5.161$, $p=.057$.

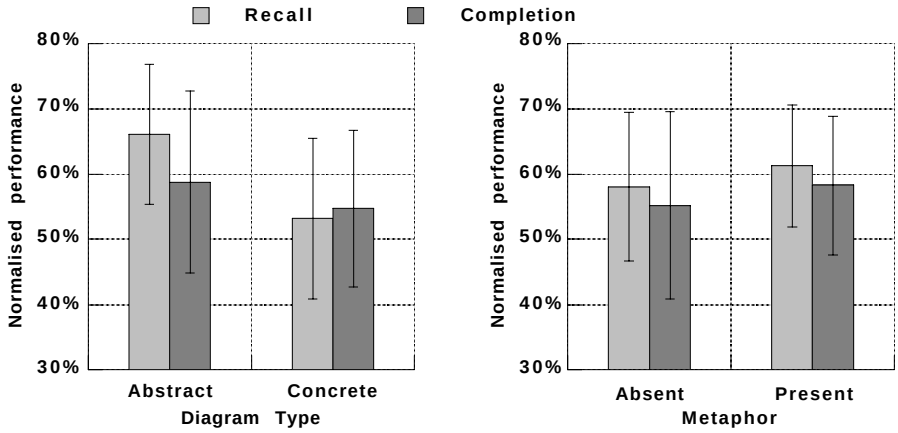


Figure 6.7. Recall and completion performance for each diagram type and metaphor

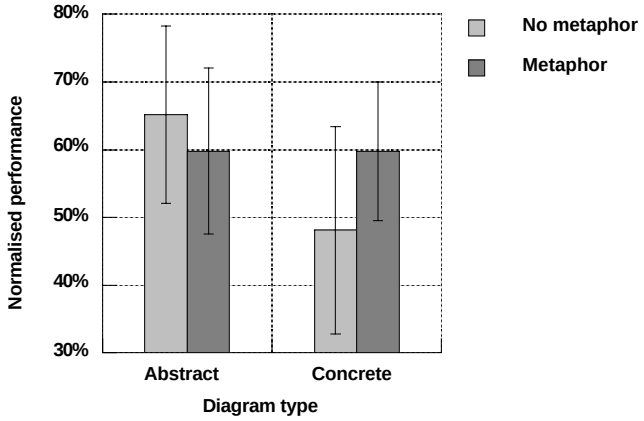


Figure 6.8. Interaction of diagram type and metaphor

As in experiment 7, I also compared the times spent reading the diagram explanations, in order to examine any strategic differences in mnemonic strategies. Reading times were again longer when metaphors were included in the explanation than when they were not, $F(1,7)=10.54$, $p<.05$. This is consistent with the fact that the metaphorical explanation texts were longer. Reading times were also longer for abstract diagram types than for concrete diagrams, $F(1,7)=19.37$, $p<.01$, but this is not the result of any difference in the length of the texts: it reflects the fact that the abstract diagrams are simply more complex, and take longer to understand with or without a metaphor. Participants tended to spend longer reading explanations of abstract diagrams when a metaphor was provided, as shown in Figure 6.9 –

this implies that they did spend time forming a metaphorical model of the more complex diagrams, but the tendency is not statistically significant, $F(1,7)=3.75$, $p=.094$.

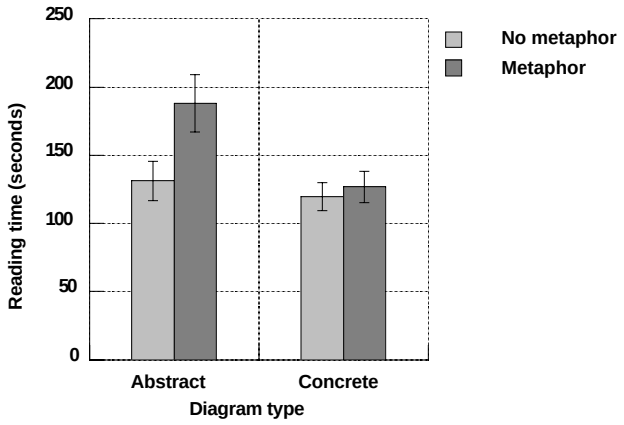


Figure 6.9. Explanation reading time: interaction of metaphor with diagram type

At the end of the booklet, participants reported the method they had used to remember symbols. Of the sixteen diagrams for which no metaphor was provided (two for each participant), participants reported for nine of them that they had constructed their own metaphors. Some of these constructed metaphors appeared to be related to the intentional design of the symbols; for example in the case of the gold mine ("symbols partly look like the job they are doing") or for the flight path ("imagined flying plane"). Other metaphors were completely original; again in the case of the gold mine, the "fork" symbol for picking up individual nuggets was described by one participant as "like a coffee bean (one nugget)" and by another as "rounded like chicken nuggets". Some mnemonic techniques were apparently verbal ("I remembered circle triangle square in order"), and one participant appeared to use synesthetic mnemonics – "a circle was a green go sign and a square a red stop sign" (the symbols were not printed in colour), and "the rock was angular and harsh".

Experiment 8A): Rating of symbol forms

In experiment 8, participants were asked to draw symbols from memory in the diagram completion task. Some of the productions were not immediately identifiable as corresponding to any of the defined symbols. The causes of this inaccuracy may be related to the fact that so many adults are unable to draw what they see. Cohen and Bennett (1997) attribute this to misperception of the object being drawn, resulting from biases in existing knowledge. In children's drawing, the ability to reproduce figures also relies on developing a repertoire of standard components (Fenson 1985) that may not be combined strictly according to the

visual appearance of a shape being copied. Whatever the cause of inaccuracy, it is quite possible that some of the inaccurate reproductions in this experiment were influenced by the instructional metaphor. If I had rated these productions myself, my familiarity with the metaphor would certainly have biased my assessment in favour of those that were consistent with the metaphor, thereby favouring implicit recall of the metaphor rather than accurate recall of the diagram. Experiment 8 was therefore followed by this independent rating exercise.

Procedure

Five raters were recruited from staff and students at the APU. None of the raters had previously seen the diagrams, their definitions or the metaphorical explanations. Each rater was given a set of photocopied pages, each one of which contained one of the sets of six symbols defined for the diagrams, but included neither any verbal explanation nor diagram context. In addition to the six original symbols, the page contained photocopies of all ambiguous productions created during the diagram completion tasks. I asked the raters to decide whether each production corresponded unambiguously to one of the symbols, and if so, which symbol.

Results

In general, the raters were conservative in identifying productions, and judged a relatively large number of symbols to be ambiguous. The majority decision from the five raters was used to score each symbol that had been produced by subjects in experiment 8. The scores based on these ratings are the ones that are reported in the results section for experiment 8.

Discussion

This experiment introduced two new diagrams where the interpretation of the diagram involved a simple spatial correspondence between the diagram layout and the problem domain, rather than a more complex abstract syntax. Tasks using these diagrams were completed far more quickly, reflecting the relative simplicity of representations based on spatial correspondence. In the more complex abstract diagrams, participants were able to recall symbols, but had greater difficulty in using them to complete partial diagrams. The reverse was true for the simple concrete diagrams – performance on completion tasks was improved relative to symbol recall tasks. Experiment 9 further investigates the distinction between symbol recall and structural comprehension tasks.

The effect of the instructional metaphor in this experiment can be considered in terms of this difference between the two diagram types. The metaphor appears to have provided a greater advantage in the case of simpler, concrete diagrams. In these diagrams the problem-solving component is reduced even further, as the metaphor is used mainly as a pictorial mnemonic, rather than as an aid to interpreting the structure of the diagram. In the complex abstract tasks, introduction of the metaphor may even impair performance as a result of the additional demands associated with interpreting the metaphor – these increased demands are reflected in longer reading times.

Experiment 7 discussed the possibility that some participants gained more advantage by developing their own explanatory metaphors, rather than reading an instructional metaphor that was provided for them. The benefits of self-generated metaphor have been reported by Carroll and Mack (1985) and by Jones (1984). In the debriefing questionnaire of this experiment, most participants did report using metaphorical mnemonic strategies even when no metaphor had been provided. These mnemonic metaphors must have been constructed while participants were reading the diagram explanations, but reading times were shorter in the cases where no metaphor was provided. These mnemonic metaphors must therefore have been constructed more quickly than the time it takes to read and interpret an existing metaphor. Furthermore these self-generated metaphors are equally effective as mnemonic devices. This is considered further in experiment 9, where more detailed pictorial content facilitates self-generated metaphors.

Experiment 9: Comparison of explicit and implicit metaphor

This experiment compares the two styles of diagrammatic metaphor that have been considered separately in the rest of this thesis. Experiments 1, 3, 5 and 6 evaluated the results of *implicit* diagrammatic metaphor: diagrams which incorporate pictorial symbols, but without explicitly describing how those symbols should be interpreted. This is the general practice in the graphical user interfaces of many commercially available software packages, anticipated by the cognitive theories of metaphorical abstract concept representation proposed by Smith (1977). Experiments 2, 7 and 8 investigated *explicit* diagrammatic metaphors; the intended interpretation was explained using instructional metaphors. Most psychological theories of metaphor use in HCI accordingly consider it to be an instructional device (Mayer 1975, Carroll & Thomas 1982, van der Veer 1990).

This experiment compares diagrams constructed from pictorial and abstract symbols, both with and without explicit descriptions of the intended metaphorical interpretation. The

observations of experiments 7 and 8 allow two hypotheses that have not been anticipated by previous theories of metaphor use. The first is that the benefits of metaphor will be mainly observed in improved recall for symbol definitions, but will not improve performance in tasks where structural interpretation of the diagram is the main task component. The second is that implicit pictorial metaphor will provide a greater advantage than explicit instructional metaphor because it will facilitate the construction of self-generated metaphors, which will provide greater benefit in recall tasks.

Notation

Participants in this experiment learned to use novel types of diagram, as in experiments 2, 7 and 8. The diagrams used in experiments 2 and 7 expressed computational concepts, while experiment 8 introduced more straightforward spatial representations (goldmine layout, and aeroplane landing path). The two spatial representations from experiment 8 were used again here, along with two new diagram types. These two also relied on conventional usage of space. One expressed spatial layout as a direct mapping. The other presented timelines running from left to right and symbols that associated height with increasing quantity. These conventions have been verified experimentally by Gattis and Holyoak (1996), who reported reduced accuracy when the conventions are not observed during graph construction, and by Tversky, Kugelmass and Winter (1991), who found that even pre-literate children tend to organise quantitative information along these axes.

The first of the new diagrams introduced in this experiment shows predicted performance of stocks over several years in the market. The diagram is laid out in a conventional tabular form, with the time axis running from left to right, as shown in Figure 6.10. Each row of the table is a time line showing predicted performance of a particular stock in future years. The symbols that can be placed along the timeline show whether the stock is expected to rise or fall, to oscillate or become unstable, and whether it is cyclical around a stable price or climbing overall.

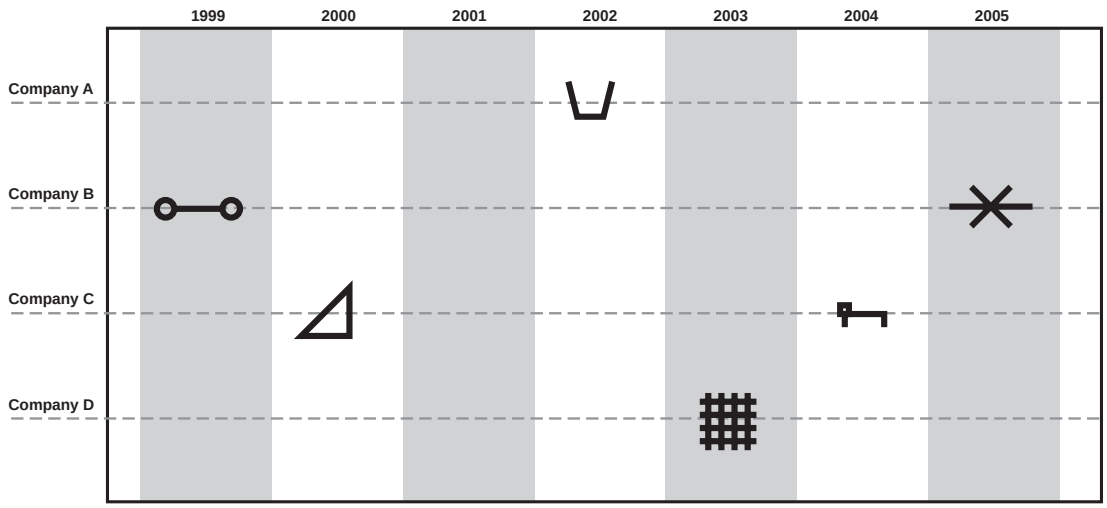


Figure 6.10. Stock market diagram.
E.g. the stock of company D is expected to climb in 2003

As in experiment 8, these symbols can be explained in terms of a systematic metaphor, where some resemblance is described between the symbol that is used and an element of the metaphor source domain. In this experiment, however, that resemblance is made far more apparent by replacing the stylised symbol with a small photograph of the actual source metaphor element. The corresponding photographs used in place of each symbol for the stock market diagram are shown in Figure 6.11. The systematic metaphor in this case is the range of motions made by playground equipment.

A seesaw represents a stock that is simply oscillating without rising. A slide represents a falling stock, and a swing is used for a stock that is oscillating, but rising higher each time. An unstable stock is represented by a rocking horse, a rising stock by a climbing frame, and a cyclical one by a roundabout.

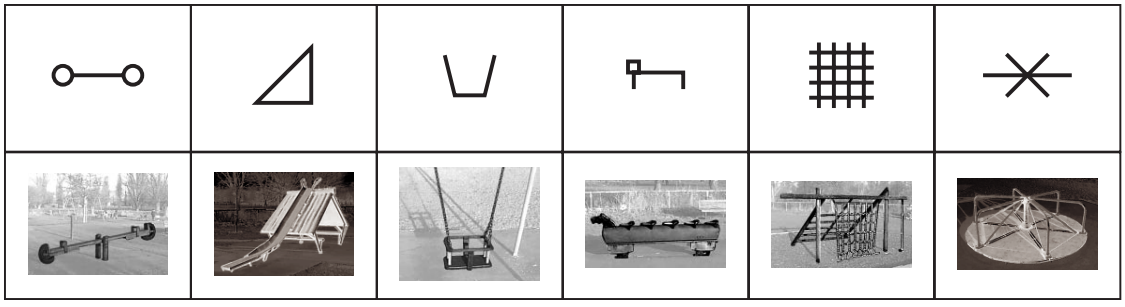


Figure 6.11. Stock market playground metaphor

Figure 6.12 shows the same stock market diagram as in Figure 6.10, but with the stylised symbols replaced by photographic icons.

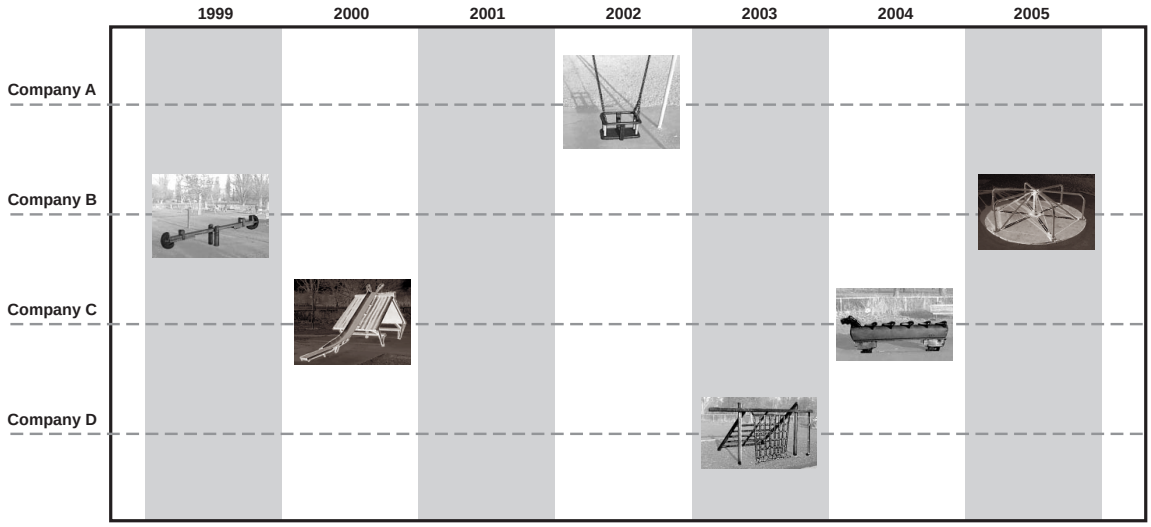


Figure 6.12. Stock market diagram with metaphorical photographs

The second new diagram expressed constraints in the layout of a newspaper front page; an example is shown in Figure 6.13. As in the previous diagram, constraints are represented by six different symbols that can be placed anywhere on the page layout. These symbols indicate attributes of the stories that should be placed in different locations: the main story of the day, an attractive photograph, an analysis story, a dull story, or stories that should be placed at the top of the page or in small gaps.

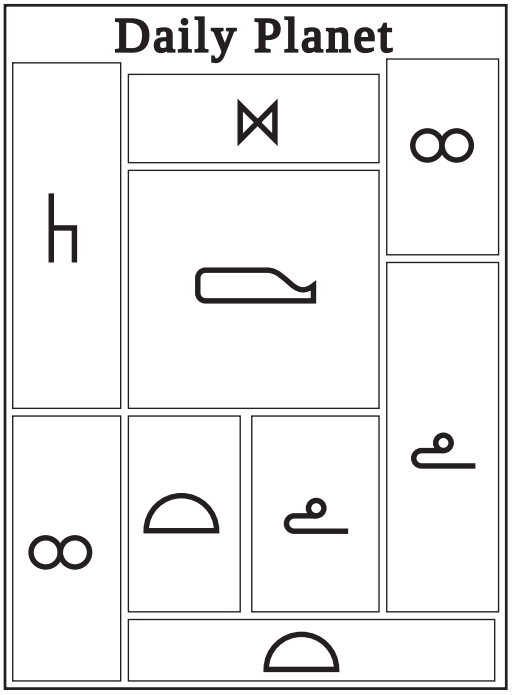


Figure 6.13. Newspaper layout diagram

The metaphorical presentation of the newspaper layout symbols is shown in Figure 6.14. The systematic basis of the metaphor comes from the attributes assigned by convention to different animals. A dull story is represented by a tortoise, a story at the top of the page by a giraffe, a story for filling small gaps by a mouse, an analysis story by an owl, a large main story by a whale, and an attractive photograph by a butterfly. As drawings of animals are more easily obtained than photographs, I used realistic line drawings in the pictorial version of the diagram.

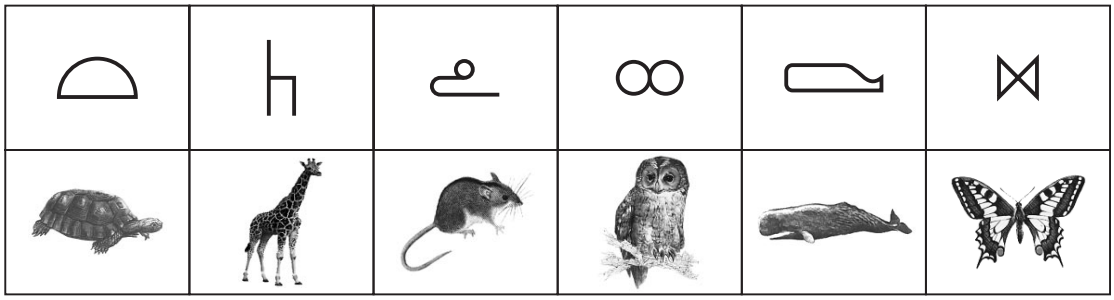


Figure 6.14. Newspaper layout animal metaphor

I also prepared pictorial versions of the two diagrams that were introduced in experiment 8. For the aeroplane landing diagram I used photographs of appropriate car controls, treated in

the same way as has been described for playground equipment. For the gold mine diagram I used photographs of cutlery, taken against a white background. These two sets of photographs are shown alongside the corresponding stylised symbols in Figures 6.15 and 6.16.

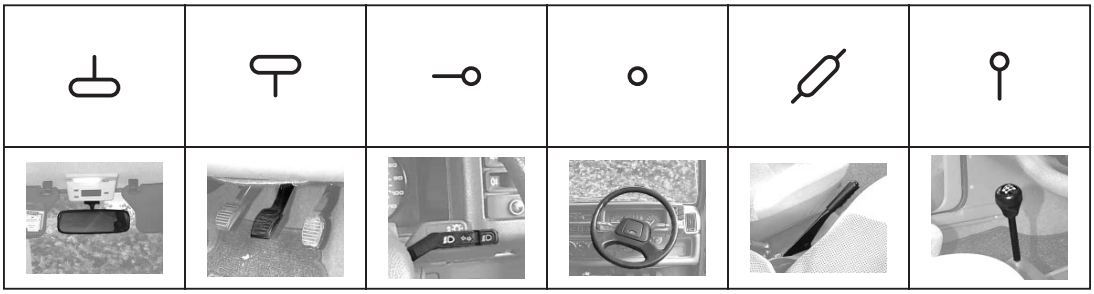


Figure 6.15. Aeroplane landing symbols and car controls metaphor

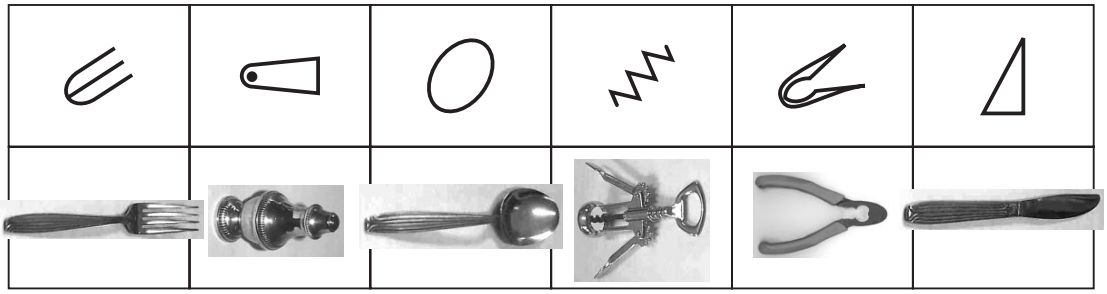


Figure 6.16. Gold mine symbols and cutlery metaphor

Tasks

Participants completed two tasks using each diagram. The first was a comprehension task similar to that used in experiments 2 and 7. In the stock market task, participants identified stocks to buy according to certain criteria. In the gold mine task, participants identified which shaft in the mine would involve the greatest total effort or profit. The tasks used for the aeroplane landing and newspaper layout diagrams involved finding inconsistencies in a complete diagram, when assessed according to a supplied set of constraints. These tasks are reproduced in appendix B.9.

The second task was the recall task previously used in experiment 8, in which all six symbols that had been used in each diagram were presented out of context, and participants wrote definitions of each symbol.

Diagram completion tasks were not included in this experiment because it was not practical for participants to complete diagrams by drawing the photographic symbols.

Equipment

As in experiments 2, 7 and 8, material was presented to participants in booklet form. Participants wrote directly in the booklet, and used a stopwatch to record the amount of time they spent working on each page.

The photographic versions of the diagram symbols were prepared by taking photographs of playground equipment, car controls and cutlery with a digital camera. I then used Adobe *Photoshop* software to mask the structural aspects of the scene that were relevant to the metaphor, and reduced the contrast of the background. The photographs then cropped to emphasise the metaphorical features, and reduced to cover an area of approximately 3 or 4 cm^2 at a resolution of 200 dpi. The animal drawings were scanned from stimuli used in another experiment at the APU, and reduced to the same size and resolution.

Hypotheses

1. That neither the implicit nor explicit metaphor will significantly improve problem solving performance.

2. That an implicit pictorial metaphor will improve recall more than explicit metaphor, because it will facilitate self-generated metaphor.

3. That reading time will be shorter when pictorial symbols are provided, indicating that generation of a metaphor is more efficient than interpretation of metaphorical instruction.

Participants and design

Twenty four participants were recruited from the APU panel of volunteers. There were no factors varied between subjects, and three independent variables within subjects. The first independent variable had two levels: the metaphor was either explicitly *present* in the verbal explanation of the diagram, or *absent*. The second independent variable was the form of symbols used as elements in the diagram: these were either *pictorial* or *stylised*. These two independent variables were balanced in a latin square design, but as in previous experiments there was a partial confound with the actual diagram. As before, this partial confound was

balanced across all participants. Performance was again tested using two different tasks: the *comprehension* and *recall* tasks described above.

There were three dependent variables: the time taken to *read* the diagram explanation, *speed* in the comprehension and recall tasks, and normalised *accuracy* scores for comprehension and recall tasks. The first hypothesis was tested in terms of speed and accuracy, the second in terms of accuracy in the recall task, and the third in terms of reading time.

Procedure

Participants followed the same time-keeping procedure as in previous experiments, recording the time when they started working on each page. All four diagrams were presented at the start of the booklet, with explicit metaphor either present or absent from the explanations as appropriate. The presentation order of the different diagrams was the same for every participant: this meant that the presentation order of the different metaphor conditions was appropriately balanced.

The presentation of the diagrams was followed either by four pages with a comprehension test for each diagram, or by four pages with a recall test for each diagram. The comprehension test in this experiment involved finding inconsistencies in a complete diagram, when assessed according to a supplied set of constraints. This style of test was used rather than the diagram completion tasks of experiment 8 because it was impractical to ask participants to complete diagrams by drawing photographic symbols. The tests for each diagram were presented in the same order as the diagrams had been explained, but the order of the two blocks of tests, comprehension and recall, was balanced across participants. As in experiment 8, a debrief questionnaire at the end of the booklet asked participants to report what technique they had used to remember each set of symbols.

Completed booklets were scored by comparison to ideal worked solutions, and marking was done while blind to the metaphor condition with which diagrams had been explained. The straightforward memory task, in which participants wrote the definition of a symbol, was scored using the same procedure as described in experiment 8. The comprehension tasks were scored by subtracting one mark for every problem constraint that was violated in the solution. Where no response was made to some parts of a question, further marks were subtracted. These were allocated so that each solution started with a possible ten marks, which were reduced to zero if no answer was given. A large number of constraint violations could result in a score below zero, however.

Results

The first hypothesis was that neither the form of the symbols nor the provision of a verbal metaphor would improve problem solving performance. Both problem solving scores and recall scores are shown in figure 6.17. Problem solving performance in tasks with an explicit verbal metaphor supplied actually tended to be poorer than for those without the verbal metaphor, although this difference was not statistically significant, $F(1,23)=0.84$, $p=.368$. There was, however, a significant improvement in performance as a result of the implicit pictorial metaphor, $F(1,23)=4.49$, $p<.05$.

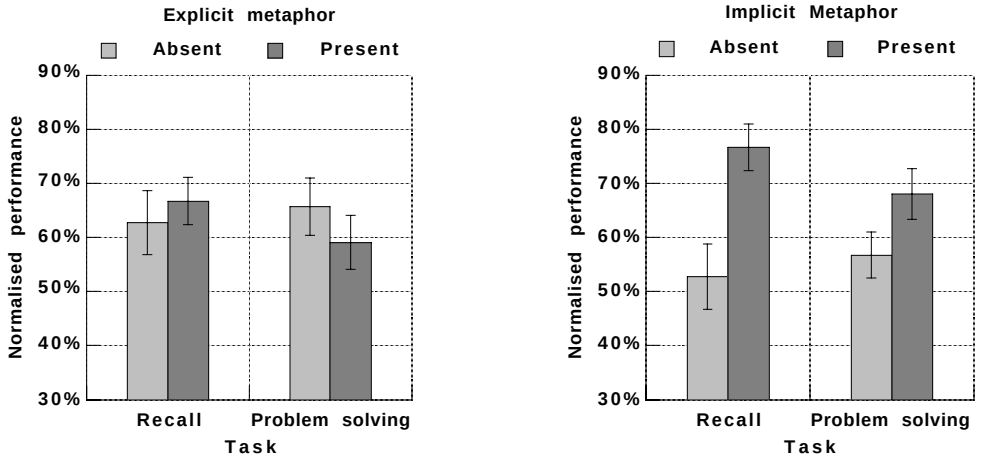


Figure 6.17. Problem solving and recall scores with implicit and explicit metaphors

The mean times taken to complete the recall and problem-solving tasks were approximately 10% slower in cases where an explicit metaphor had been provided, although this was not statistically significant for either recall or problem solving, $F(1,23)=3.49$, $p=.121$ and $F(1,23)=2.59$, $p=.074$ respectively.

The second hypothesis was that the pictorial symbols of the implicit metaphor would selectively improve recall performance. This was the largest effect observed in the experiment, $F(1,23)=26.09$, $p<.001$. Unlike the problem solving scores, inclusion of explicit metaphor did produce a slight trend toward improving the recall score, but the effect of explicit metaphor is not significant, $F(1,23)=0.90$, $p=.353$.

The third hypothesis was that reading time would be shorter when pictorial symbols are used rather than abstract ones. This was the case, as shown in figure 6.18, $F(1,23)=5.51$, $p<.05$. The difference was larger than the difference in length of the text resulting from presence of an explicit metaphor. The effect of pictorial symbols on reading time also tended to be larger

when no explicit metaphor was included in the explanation, although the interaction was not significant, $F(1,23)=1.14$, $p=.297$. This supports the conclusion made in experiment 7, that users of diagrams can generate mnemonic metaphors relatively quickly compared to the time that it takes to understand a metaphor provided with the diagram explanation.

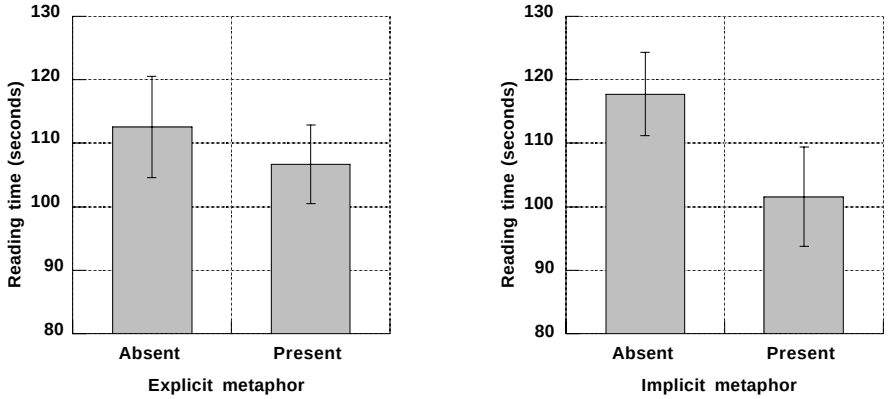


Figure 6.18. Variation in reading time with implicit and explicit metaphors

The presentation of results for experiment 8 included a simple count of the number of occasions on which participants described a mnemonic technique involving their own metaphorical system. In this experiment, each of the 24 participants received instructions without a metaphor for one diagram with pictorial symbols, and for one diagram with geometric symbols. Of the 24 pictorial cases, 20 participants reported the creation of a metaphor based on the pictures. Of the 24 geometric cases, only 9 participants reported the creation of a metaphor. As in experiment 8, the metaphors developed for geometric symbols were often imaginative. The grid that represented a climbing frame for rising share prices was remembered by one participant as a "prison gate to *lock in* profits" and by another as " a *grate* time to buy". The non-metaphorical strategies that were reported included non-specific verbal strategies ("associate a word with each symbol") and sequential strategies ("tried to remember them in order"). Of the four pictorial cases where a metaphor was not reported, one participant reported a verbal strategy ("talked myself through them"), one a spatial strategy ("tried to remember positions on the page"), one indeterminate ("by association") and one simple failure ("I didn't construct a method").

I also tested for any effect of varying the order of problem solving and recall tasks, to determine whether the presentation of problem solving tasks before recall tasks in experiment 8 may have improved recall performance as a result of rehearsal effects unrelated to the metaphor treatment. There was no significant difference between any of the four independent variables in cases where recall was tested before and after problem solving: *t*-tests of order

effects on scores for problem solving and recall respectively were $t(22)=0.220$, $p=.82$ $t(22)=0.501$, $p=.62$, while *t*-tests on the times taken to complete these tasks were also non-significant: $t(22)=0.762$, $p=.45$ and $t(22)=0.923$, $p=.36$ respectively.

Discussion

The results of this experiment confirm the hypotheses regarding the relative benefits of implicit pictorial metaphor and explicit explanatory metaphor. Metaphor in diagrams is mainly a mnemonic aid rather than a structural aid to interpretation of the diagram. Furthermore, this mnemonic aid is more pronounced where the pictorial content allows users to generate their own metaphors, rather than when an explicit instructional metaphor is provided.

The mnemonic advantage of pictorial material is predicted by several theoretical models. Paivio's dual coding model predicts that associating any concrete image with the presentation of verbal information will improve recall (Paivio 1971,1983). Marschark and Hunt (1985) have demonstrated that a high rating of imageability of a verbal metaphor is a good predictor for later free recall of that metaphor. Glenberg and Langston (1992) explain the value of illustrations accompanying text as resulting from the formation of a *richer* mental model, where the additional information in the illustration facilitates the noticing of many relationships that might only be implicit in the text (although Langston, Kramer & Glenberg (1998) have recently reconsidered the assumption that noticing results from mental image representations – it seems that implicit spatial relationships in simple verbal descriptions are seldom noticed). In any case, mental models constructed as self-generated metaphors are likely to be richer than those formed while interpreting texts.

The effect on performance of changing the degree of pictorial detail, and hence varying the amount of information provided in pictures, has been investigated before. The work of D. Schwartz (1995) was reported in chapter 4 – he found that lower fidelity representations were more likely to be analysed symbolically rather than by mental animation strategies. Goolkasian (1996) reports that comparative judgements made from simple geometric stimuli are faster than those made from verbal stimuli, whereas Potter et. al. (1986), as discussed in experiment 8, find that pictorial stimuli take longer to process than words. Nelson, Metzler and Reed (1974) compared recognition performance for words, line drawings and photographs. They found an advantage of pictures over words, but no further advantage from increasing pictorial detail (although their black and white photographs were relatively poor compared to modern experimental stimuli). Ryan and C.ÊSchwartz (1956) found that caricatures were interpreted faster than either line drawings or photographs – this seems

unsurprising, as the caricatures made salient features more prominent. These rather mixed results do not provide a firm foundation for generalisation to either diagrams or to HCI. Strothotte and Strothotte (1997) note that, although graphical symbols in a user interface must ultimately be interpreted by convention, the benefits of representational detail are disputed. They quote Dale (1969) as recommending realism for educational purposes, while Travers (1964, cited by Strothotte & Strothotte) criticises this practice as the "worship of a false god".

An interesting investigation of pictorial detail in user interface icons that does support the findings of this experiment is reported by A.ÊGreen and Barnard (1990). They observed the time that users took to select a specific icon from an array of distractors. The icons in the array were either abstract symbols or representational pictures. They found that search times for the representational pictures were initially slower than for abstract symbols, but that improvement with practice was significantly greater for representational pictures. Rohr (1987) has also investigated two alternative models of pictorial information in user interfaces. The first is derived from Jackendoff's theory of conceptual semantics (1983), in which the structural categories of the physical world are applied systematically to the interface representation. The second is derived from Paivio's dual coding theory (1971), in which images provide mnemonic codes. Rohr found that experimental participants could be divided into two groups: visualisers were more likely to improve their recall using pictures as a result of dual coding; formalisers were more likely to apply structural categories to the user interface, but they did this using verbal strategies rather than visual strategies.

These two studies support the results found in this experiment – Green and Barnard report that representational detail supports learning, and Rohr reports that pictorial icons are more likely to be used to assist recall than they are to support systematic metaphors. They are relatively unusual amongst previous studies of user interface metaphor, however. Most previous research has emphasised the benefits of systematic metaphor in designing graphical or diagrammatic user interfaces. The results found here suggest that simple mnemonic effects are far more significant.

Chapter 7: Conclusions

Then thought I to understand this:
but it was too hard.

Psalm 73:15

This thesis set out to investigate a widely held belief about the diagrams in graphical user interfaces: that they are interpreted in terms of metaphor. As with other types of diagram, user interfaces cannot be treated simply as if they are a form of language, or as if they are objects to be perceived without interpretation. The user of any diagram must interpret it according to the intention with which it was constructed (Ittelson 1996), and there are many cases in which diagrams are intended as figurative rather than literal representations. The figurative intention in a diagram might be regarded either as analogical, transferring the structure of graphical variables to the domain of a problem (Bertin 1981, Larkin & Simon 1987), or as allegorical, embodying abstractions as some analogue of objects in physical space (Jackendoff 1983, Johnson 1987).

When user interface design textbooks recommend the use of metaphor as a basis for new designs they do not investigate these theoretical alternatives too carefully. Such investigation might even seem foolhardy, because empirical research projects in HCI often fail to find significant benefits when metaphors are compared to non-metaphorical interfaces (Simpson & Pellegrino 1993, Potosnak 1988). At a time when many technical resources are being devoted to extending allegorical metaphor into three dimensional virtual worlds, it is worrying that such projects similarly fail to find advantages of 3-D metaphors (e.g. Sutcliffe & Patel 1996).

The demonstrable advantages of graphical user interfaces, as with many types of diagram, can be explained in other terms. Direct manipulation – representing abstract computational entities as graphical objects that have a constant location on the screen until the user chooses to move them – facilitates reasoning about the interface by reducing the number of possible consequences of an action (Lindsay 1988). Similar constraints provide the cognitive benefits of most types of diagrammatic representational system (Stenning & Oberlander 1995), and valuable new diagrams can be invented by selecting geometric constraints that apply to a specific abstraction (e.g. Cheng 1998). Where these types of cognitive benefits arise from a notational system, there is little need to invoke theories of metaphor to explain them. Many of the Cognitive Dimensions of Notations (Green 1989, Green & Petre 1996) are little affected by the degree to which the notation is intended to be figurative.

These pragmatic principles for the analysis of notations are only gradually becoming accepted among designers of new diagrammatic user interfaces. Chapter 3 reported a survey of research publications describing visual programming languages. These publications reflected widespread superlativist theories of diagram use (Green, Petre & Bellamy 1991). They also appeared to reflect a consensus of opinion within this community about the nature of diagram use – much of which can be attributed to the pioneering work of Smith (1977), where he argued that visual images support creative abstract thought by metaphorical processes. Despite this consensus, two surveys of professional programmers showed that these beliefs appear to be restricted to the research community. Programmers who have no specific allegiance to visual programming are sceptical about any potential benefits – probably simple professional conservatism. Those who do use a visual language professionally are not sceptical, but they often describe its pragmatic advantages and disadvantages in terms of notational features that are better explained by the Cognitive Dimensions of the language than by theories of metaphor.

Review of experimental findings

Visual programming languages have often been described as suitable for inexperienced programmers because the diagram expresses the behaviour of the program in terms of some metaphorical virtual machine. In chapter 4, this was tested by making the metaphor more or less available to inexperienced programmers, and evaluating the resulting changes in performance by comparison to experienced programmers. In experiment 1, the metaphor was conveyed by making the elements of the diagram more pictorial, while in experiment 2 the metaphor was explicitly described in instructional material. In neither case did the provision of the metaphor result in appreciable performance improvements relative to more experienced programmers, despite the fact that the computational concepts included in the diagrams of experiment 2 were heavily disguised, and that the diagrams were equally novel to all participants.

Early research publications in HCI regularly equated graphical user interfaces with metaphor on a basic cognitive level: “the use of appropriate verbal metaphors was enhanced by the use of diagrams (which are of course also metaphors)” (Carroll & Thomas 1982, p. 111); “images are metaphors for concepts” (Smith 1977, p. 23); “visual imagery is a productive metaphor for thought” (ibid. p. 6); “concepts in the short term memory are metaphorical images derived from sense perceptions” (ibid. p. 11). The role of visual imagery in the production of diagrams was investigated in the experiments of chapter 5. These found little

evidence for the use of visual imagery when planning diagrams. Experiment 3 did find some evidence that a physical metaphor might inhibit abstract reasoning, but this appears to have been an artefact of a specific combination of stimulus and task, as several attempts to replicate the effect failed.

Whereas experiment 6 found that using metaphorical elements in a diagram had less effect on solution elaboration than either task complexity or experimental demand, experiment 5 failed even to find any effect resulting from the use of severely incongruent metaphors. The tasks used in these experiments were admittedly simple by comparison to the demands of design and problem-solving in many computer applications, but they suggest that many people construct diagrams without systematic use of either mental imagery or physical metaphor.

The experiments in chapter 6 returned to the question of metaphor as an instructional device. A number of variations on experiment 2 found that metaphor did provide some advantages in learning the conventions of a new diagram. Rather than supporting complex problem solving, however, those advantages seemed to be simple mnemonic ones. Performance in comprehension tasks was scarcely improved by systematic metaphors that explained diagrams in terms of virtual machines and other metaphorical conventions. Furthermore, the mnemonic advantage was equally great where participants created their own metaphors rather than being given an explicit instructional metaphor. If the diagram included pictorial elements, this facilitated self-generated metaphor – a factor that seems to have greater mnemonic value than systematic explanations.

Related results

These findings are consistent with a small number of previous studies. Marschark and Hunt (1985) found superior recall of verbal metaphors in cases when it was easy to form a concrete visual image of the metaphor subject, but inferior recall of metaphors with strong semantic relations. If theories of verbal metaphor can be extended to diagrams, their work supports the contention that diagrammatic metaphor brings more advantage for mnemonic tasks than for systematic problem solving. Payne (1988) found that metaphorical instruction had a mnemonic benefit when learning a command language, although this effect was smaller than the benefit of making the language itself systematic and consistent.

Martin and Jones (1998) observed that memory for even familiar symbolic conventions is influenced by people constructing their own systematic interpretations. These interpretations will often reflect some schema that was not intended in the original symbol design, resulting

in surprisingly inaccurate memory among the general population for common symbols such as road signs.

Self-generated metaphor has been employed to great advantage in an educational variation of the visual programming language. Ford (1993) asked introductory computing students to create their own animated visual language, metaphorically expressing fundamental computational concepts. He reported significant benefits to his students. On the basis of the experimental evidence reported in this thesis, such an approach would be expected to be far more valuable than many proposed visual programming languages.

Implications

The findings described in this thesis have often encountered scepticism from other HCI researchers. Metaphor is so widely recognised as forming the basis for graphical user interfaces that it might seem unreasonable to question this assumption. Metaphor is almost always recommended as a basis for design in user interface textbooks, and publications describing the benefits of metaphor have appeared in the research literature for many years. Substantial commercial empires are attributed to the success of the "desktop metaphor", and millions of personal computer users have experienced dramatic improvements in usability when moving to this interface from previous generations of command-line system.

My contention is that the benefits of the "desktop metaphor" are misattributed. These systems were the first commercial products to allow direct manipulation of elements on the display, and I believe that their benefits derive almost completely from direct manipulation rather than from metaphor. Indeed, I have encountered anecdotal evidence that personal computer users outside the computer industry are often completely unaware of the intended metaphor in the systems they use. They understand "Windows" to be an arbitrary trade name rather than a metaphorical description of some aspect of the user interface (perhaps someone might compare the usability advantages of the "Apple" metaphor for fruitier user interfaces).

To those who have experienced the benefits of direct manipulation, and are aware of the supposed benefits of user interface metaphor, it is still difficult to explain those benefits in terms of cognitive theories. There are several competing theories of metaphor, with differences that may appear overly subtle by comparison to the obvious benefits of direct manipulation. Some respected cognitive scientists explicitly discount the application of their theories to computer interfaces (e.g. Gentner, Falkenhainer & Skorstad 1988), but this leaves

the HCI researcher with numerous other theories to choose from, some of which claim a very strong link to diagram interpretation (e.g. Lakoff 1993).

The most important factor in the general acceptance of diagrammatic metaphor as a design principle in HCI, however, is the fact that it has not been empirically tested. The current project appears to have been the first attempt to isolate diagrammatic metaphor (rather than more general instructional metaphor) as a factor in controlled experiments. Previous experiments have compared metaphorical graphical interfaces to non-metaphorical interfaces, with disappointing results (Potosnak 1988). It has always been possible, however, to attribute those negative results to other aspects of the systems that were being compared (e.g. Simpson & Pellegrino 1993), or to confounding individual differences in the experimental sample (e.g. Rohr 1987).

The findings of this study do suggest some limited advantages from employing metaphor in diagrams – pictorial metaphor brings some mnemonic advantages, especially if the pictures are realistic (more realistic than those usually included in graphical user interfaces). In the absence of strong evidence for the broader benefits of metaphor, it might be wiser for user interface designers to turn to empirical findings that have shown advantages resulting from other aspects of notation design – particularly the correspondence between geometric structure, tools for manipulating those structures, and cognitive information processing tasks.

Further Investigation

Most of the experiments described in this thesis have taken at face value some of the "superlativist" claims of the HCI and visual languages community. In particular, they have tested the assumption that diagrams are universally beneficial in problem solving and design. This is obviously not the case – even within the scope of these studies, a simple distinction between "experts" and "novices" has revealed not universal benefits, but a large difference between individuals with different amounts of experience. Some of this difference may well be attributable to imagery strategies, as found in studies of experts by Hishitani (1990) and Saariluoma and Kalakoski (1997). Other studies have also found differences between the strategies of individuals given the opportunity to employ imagery when using diagrammatic representations (Schwartz & Black 1996b, Stenning & Gurr 1997). It would be valuable to investigate the relationship between individual strategies and the type of metaphorical diagrams studied here – the result of such a study may well explain the vehemence of superlativist positions, as well as the historical context of diagram research within the imagery debate.

This study also shares a practical deficiency with many other experimental studies in psychology and HCI. Although it purports to investigate learning effects, the period of learning in each experimental trial is extremely short – the longest experiment reported here lasted two hours, and almost all were shorter than an hour. No real design notation or user interface would be learned in such a short time, and as a consequence the experimental tasks have been almost trivially simple. Other experiments have shown significant effects of practice when using similar notations (Scaife & Rogers 1996, Schwartz & Black 1996a, van der Veer 1990). Despite this weakness, the current study is valuable because many researchers have claimed large and immediate effects for the benefits of metaphor. The conclusion of this study is that, although there may well be effects to be observed, they are not necessarily large or immediate.

The notations used in this study have been rather artificially simple, in order to be acquired and applied within an experimental session. They have also been made unlike any widely used diagrammatic notation, in order not to introduce a confound of individual experience beyond the basic level of professional background (Cox 1997). For any real notation, however, many of its elements are based on diagrammatic conventions that are already familiar to users from other contexts (S. Smith 1981, Wang, Lee & Zeevat 1995). Consistent application of these conventions is an essential aspect of the professional skills of information designers and other developers of new notations. This is also an area that deserves further investigation.

Finally, this study has only partially explained the almost universal acceptance of metaphor as a basis for user interface design. It is possible that part of this popularity results from confusion between the functions of metaphor and direct manipulation in HCI. It is also possible that the pioneering work of D.C. Smith (1977), popularised and achieving huge commercial success through the Xerox Star, Apple Macintosh, and Microsoft Windows, has had more influence than is justified by the psychological evidence he presented. It is still possible, however, that the advantages attributed to metaphor are really due to some unexplored aspect of systematic conceptual metaphors. One candidate for this is the principle of *abstraction congruence* proposed by Simos and Blackwell (1998), which will be the subject of extended investigation in the near future (Blackwell 1998).

Chapter 8: References

Adelson, B. (1981). Problem solving and the development of abstract categories in programming languages. *Memory & Cognition*, **9**(4), 422-433.

Akoumianakis, D. & Stephanis, C. (1997). Supporting user-adapted interface design: The USE-IT system. *Interacting with Computers*, **9**(1), 73-104.

Anderson, J.R. (1996). ACT: A simple theory of complex cognition. *American Psychologist*, **51**(4), 355-365.

Apple Computer, Inc. (1992). *Macintosh Human Interface Guidelines*. Reading, MA: Addison-Wesley.

Aristotle (1927). *Poetics*. (W.H. Fyfe, Trans.) London: William Heinemann.

Arnheim, R. (1970). *Visual Thinking*. London: Faber and Faber.

Barker, P.G. & Manji, K.A. (1989). Pictorial dialogue methods. *International Journal of Man-Machine Studies*, **31**(3), 323-347.

Barnard, P. & Marcel, T. (1978). Representation and understanding in the use of symbols and pictograms. In R. Easterby & H. Zwaga (Eds.), *Information Design*. Chichester: John Wiley and Sons, pp. 37-75.

Baroth, E. & Hartsough, C. (1995). Visual programming in the real world. In M. Burnett, A. Goldberg & T. Lewis (Eds.), *Visual Object-Oriented Programming Concepts and Environments*. Greenwich, CT: Manning, pp. 21-42.

Bartlett, F.C. (1932). *Remembering: A study in experimental and social psychology*. Cambridge, Cambridge University Press.

Barwise, J. & Etchemendy, J. (1990). Information, infons and inference. In R. Cooper, K. Mukai & J. Perry (Eds.), *Situation Theory and its Applications: Volume 1***.** (CSLI Lecture Notes Number 22). Stanford: CSLI Publications, pp. 33-78.

Barwise, J. & Perry, J. (1983). *Situations and attitudes*. Cambridge, MA: MIT Press.

Bauer, M.I. & Johnson-Laird, P.N. (1993). How diagrams can improve reasoning. *Psychological Science*, **4**(6), 372-378.

Beck, B.E.F. (1978). The metaphor as a mediator between semantic and analogic modes of thought. *Current Anthropology*, **19**(1), 83-97.

Bennett, K.B. & Flach, J.M. (1992). Graphical displays: Implications for divided attention, focused attention and problem solving. *Human Factors*, **34**(5), 513-533.

Bent, I.D. (1980). Notation – I: General, II: Notational systems. In S. Sadie (Ed.), *The new Grove dictionary of music and musicians*. London: Macmillan, pp. 333-344.

Berkeley, G. (1705/1910). *A new theory of vision*. London: J.M. Dent & Sons.

Berry, D.C. (1990). Talking about cognitive processes. In K.J. Gilhooly, M.T.G. Keane, R.H. Logie & G. Erdos (Eds.), *Lines of Thinking: Reflections on the psychology of thought, Volume 2*. Chichester: John Wiley and Sons, pp. 87-98.

Bertin, J. (1981). *Graphics and Graphic Information Processing*. (Tr. W.J. Berg & P. Scott) Berlin: Walter de Gruyter.

Beveridge, M. & Parkins, E. (1987). Visual representation in analogical problem solving. *Memory & Cognition*, **15**(3), 230-237.

Black, M. (1993). More about metaphor. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 19-41.

Blackwell, A.F. (1989). Spatial reasoning with a qualitative representation. *Knowledge-Based Systems*, **2**(1), 37-45.

Blackwell, A.F. (1993). Bottom-up design and this thing called an 'object'. *EXE Magazine*, **8**(7), 28-32.

Blackwell, A.F. (1996a). Metaphor or analogy: How should we see programming abstractions? In P. Vanneste, K. Bertels, B. De Decker & J.-M. Jaques (Eds.), *Proceedings of the 8th Annual Workshop of the Psychology of Programming Interest Group*, pp. 105-113.

Blackwell, A.F. (1996b). Metacognitive theories of visual programming: What do we think we are doing? *Proceedings IEEE Symposium on Visual Languages*. Los Alamitos, CA: IEEE Computer Society Press, pp. 240-246.

Blackwell, A.F. (1996c). Do programmers agree with computer scientists on the value of visual programming? In A. Blandford & H. Thimbleby (Eds.), *Adjunct Proceedings of the 11th British Computer Society Annual Conference on Human Computer Interaction, HCI'96*. British HCI Group, pp. 44-47.

Blackwell, A.F. (1996d). Chasing the intuition of an industry: Can pictures really help us think? In M. Ireland (Ed.), *Proceedings of the first Psychology of Programming Interest Group Postgraduate Student Workshop*, pp. 13-24.

Blackwell, A.F. (1997a). Correction: A picture is worth 84.1 words. In C. Kann (Ed.), *Proceedings of the First ESP Student Workshop*, pp. 15-22.

Blackwell, A.F. (1997b). Diagrams about thoughts about thoughts about diagrams. In M. Anderson (Ed.), *Reasoning with Diagrammatic Representations II: Papers from the AAAI 1997 Fall Symposium*. Technical Report FS-97-02. Menlo Park, CA: AAAI Press, pp. 77-84.

Blackwell, A.F. (1998). *New paradigms for visual interaction*. EPSRC Research Proposal Case for Support.

Blackwell, A.F. (Ed.). (1997). *Thinking with diagrams discussion papers*. First Conference on Thinking with Diagrams. Portsmouth, England.

Blackwell, A.F. & Engelhardt, Y. (1998). A taxonomy of diagram taxonomies. In *Proceedings of Thinking with Diagrams 98: Is there a science of diagrams?* pp. 60-70.

Blackwell, A.F., Whitley, K.N., Good, J. & Petre, M. (in press). Programming in pictures, pictures of programs. In A. Blackwell (Ed.), Thinking with Diagrams [Special issue]. *Artificial Intelligence Review*.

Bødker, S. (1991). *Through the interface: A human activity approach to user interface design*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Boehm-Davis, D.A., Fox, J.E. & Philips, B.H. (1996). Techniques for exploring program comprehension. In W.D. Gray & D.A. Boehm-Davis (Eds.), *Empirical Studies of Programmers: Sixth Workshop*. Norwood, NJ: Ablex, pp. 3-38.

Bonar, J. & Soloway, E. (1985). Preprogramming knowledge: A major source of misconceptions in novice programmers. *Human-Computer Interaction*, **1**(2), 133-161.

Bonar, J.G. & Liffick, B.W. (1990). A visual programming language for novices. In S.-K. Chang (Ed.), *Principles of Visual Programming Systems*. Prentice Hall, pp. 326-366.

Booth, S. (1992). The experience of learning to program. Example: recursion. *Proceedings of the 5th Workshop of the Psychology of Programming Interest Group:* INRIA, pp. 122-145.

Bottoni, P., Costabile, M.F., Levialdi, S. & Mussio, P. (1996). A visual approach to HCI. *SIGCHI Bulletin*, **28**(3), 50-55.

Bower, G.H., Karlin, M.B. & Dueck, A. (1975). Comprehension and memory for pictures. *Memory & Cognition*, **3**(2), 216-220.

Brandimonte, M.A., Schooler, J.W. & Gabbino, P. (1997). Attenuating verbal overshadowing through color retrieval cues. *Journal of Experimental Psychology: Learning, Memory & Cognition*, **23**(4), 915-931.

Brandt, S. A. & Stark, L.W. (1997). Spontaneous eye movements during visual imagery reflect the content of the visual scene. *Journal of Cognitive Neuroscience*, **9**(1), 27-38.

Brown, M.H. & Sedgewick, R. (1984). A system for algorithm animation. *ACM Computer Graphics*, **18**(3), 177-186.

Buckingham-Shum, S.J., MacLean, A., Bellotti, V.M.E. & Hammond, N.V. (1997). Graphical argumentation and design cognition. *Human-Computer Interaction*, **12**(3), 267-300.

Burnett, M., Goldberg, A. & Lewis, T. (Eds.). (1995). *Visual object-oriented programming concepts and environments*. Greenwich, CT: Manning.

Burnett, M.M. & Ambler, A.L. (1994). Interactive visual data abstraction in a declarative visual programming language. *Journal of Visual Languages and Computing*, 5(1), 29-60.

Burnett, M.M., Baker, M., Bohus, C., Carlson, P., Yang S. & van Zee, P. (1995). Scaling up visual programming languages. *IEEE Computer*, 28(3), 45-54.

Cacciari, C. & Glucksberg, S. (1995). Understanding idioms: do visual images reflect figurative meanings? *European Journal of Cognitive Psychology*, **7**(3), 283-305.

Cañas, J.J., Bajo, M.T. & Gonsalvo, P. (1994). Mental models and computer programming. *International Journal of Human-Computer Studies*, **40**(5), 795-811.

Carpenter, P.A. & Shah, P. (1998). A model of the perceptual and conceptual processes in graph comprehension. *Journal of Experimental Psychology: Applied*, **4**(2), 75-100.

Carroll, J.M & Olson, J.R. (1988). Mental models in human-computer interaction. In M. Helander (Ed.), *Handbook of Human-Computer Interaction*. Elsevier., pp. 45-66.

Carroll, J.M, Mack, R. L. & Kellogg, W. A. (1988). Interface metaphors and user interface design. In M. Helander (Ed.), *Handbook of Human-Computer Interaction*. Elsevier, pp. 67-86.

Carroll, J.M. & Mack, R.L. (1985). Metaphor, computing systems and active learning. *International Journal of Man-Machine Studies*, **22**(1), 39-57.

Carroll, J.M. & Thomas, J.C. (1982). Metaphor and the cognitive representation of computing systems. *IEEE Transactions on Systems, Man and Cybernetics*, **12**(2), 107-116.

Carroll, J.M., Thomas, J.C. & Malhotra, A. (1980). Presentation and representation in design problem-solving. *British Journal of Psychology*, **71**, 143-153.

Carswell, C.M. & Ramzy, C. (1997). Graphing small data sets: Should we bother? *Behaviour and Information Technology*, **16**(2), 61-71.

Casey, M.B. (1996). Understanding individual differences in spatial ability within females: A nature/nurture interactionist framework. *Developmental Review*, **16**(3), 241-260.

Casey, M.B., Winner, E., Benbow, C., Hayes, R. & DaSilva, D. (1993). Skill at image generation: Handedness interacts with strategy preference for individuals majoring in spatial fields. *Cognitive Neuropsychology*, **10**(1), 57-77.

Catarci, T., Costabile, M.F. & Matera, M. (1995). Which metaphor for which database? In M.A.R. Kirby, A.J.Dix & J.E.Finlay (Eds.), *People and Computers X (Proceedings HCI '95)*. Cambridge University Press, pp. 151-165.

Chambers, D. & Reisberg, D. (1985). Can mental images be ambiguous? *Journal of Experimental Psychology: Human Perception and Performance*, **11**(3), 317-328.

Chandler, P. & Sweller, J. (1996). Cognitive load while learning to use a computer program. *Applied Cognitive Psychology*, **10**(2), 151-170.

Chang, B.-W., Ungar D. & Smith, R.B. (1995). Getting close to objects. In M. Burnett, A. Goldberg & T. Lewis, (Eds.), *Visual Object-Oriented Programming Concepts and Environments*. Greenwich, CT: Manning, pp. 185-198.

Chang, S.-K. (1987). Visual languages: a tutorial and survey. *IEEE Software*, **4**(1), 29-39.

Chang, S.-K. (1990). Principles of visual languages. In S-K. Chang, (Ed.) *Principles of Visual Programming Systems*, Englewood Cliffs, NJ: Prentice-Hall, pp. 1-59.

Chang, S.-K. (Ed.). (1990a). *Principles of visual programming systems*. Englewood Cliffs, NJ: Prentice-Hall.

Chang, S.-K. (Ed.). (1990b). *Visual languages and visual programming*. New York: Plenum Press.

Chang, S.-K., Costagliola, G., Pacini, G., Tucci, M., Tortora, G., Yu B. & Yu, J.S. (1995). Visual-language system for user interfaces. *IEEE Software*, **12**(2), 33-44.

Chechile, R.A., Anderson, J.E., Krafczek, S.A. & Coley, S.L. (1996). A syntactic complexity effect with visual patterns: Evidence for the syntactic nature of the memory representation. *Journal of Experimental Psychology: Learning, Memory & Cognition*, **22**(3), 654-669.

Chee, Y. S. (1993). Applying Gentner's theory of analogy to the teaching of computer programming. *International Journal of Man Machine Studies*, **38**(3), 347-368.

Cheng, P.C. (1998). AVOW diagrams: A novel representational system for understanding electricity. In *Proceedings Thinking with Diagrams 98: Is there a science of diagrams?* pp. 86-93.

Choi, S. & Bowerman, M. (1991). Learning to express motion events in English and Korean: The influence of language-specific lexicalisation patterns. *Cognition*, **41**(1-3), 83-121.

Clark, H.H. & Chase, W.G. (1972). On the process of comparing sentences against pictures. *Cognitive Psychology*, **3**, 472-517.

Cohen, D.J. & Bennett, S. (1997). Why can't most people draw what they see? *Journal of Experimental Psychology: Human Perception and Performance*, **23**(3), 609-621.

Cohen, L.J. (1993). The semantics of metaphor. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 58-70.

Costagliola, G., De Lucia, A., Orefice S. & Tortora, G. (1995). Automatic generation of visual programming environments. *IEEE Computer*, **28**(3), 56-66.

Cox, B.J. (1986). *Object oriented programming: An evolutionary approach*. Addison Wesley.

Cox, P.T. & Pietrzykowski, T. (1988). Using a pictorial representation to combine dataflow and object-orientation in a language independent programming mechanism. In *Proceedings International Computer Science Conference, Hong Kong*, pp. 695-704.

Cox, R. (1997). Representation interpretation versus representation construction: An ILE-based study using switchERII. In *Proceedings of the 8th World Conference of the Artificial Intelligence in Education Society (AI-ED 97)*. Amsterdam: IOS Press, pp. 434-441.

Cox, R. & Brna, P. (1995). Supporting the use of external representations in problem solving: the need for flexible learning environments. *Journal of Artificial Intelligence in Education*, **6**(2), 239-302.

Culler, J. (1976). *Saussure*. Glasgow: Collins.

Cunniff, N. & Taylor R.P. (1987). Graphical vs. textual representation: An empirical study of novices' program comprehension. In G.M. Olson, S. Sheppard & E. Soloway (Eds.), *Empirical Studies of Programmers: Second Workshop*. Norwood, NJ: Ablex, pp. 114-131.

D'Esposito, M., Detre, J.A., Aguirre, G.K., Stallcup, M., Alsop, D.C., Tippet, L.J. & Farah, M.J. (1997). A functional MRI study of mental image generation. *Neuropsychologia*, **35**(5), 725-730.

Dale, E. (1969). *Audiovisual methods in teaching (3rd edition)*. New York, Holt, Rhinehart & Winston.

Davies, S.P. (1993). Models and theories of programming strategy. *International Journal of Man Machine Studies*, **39**(2), 237-268.

Davies, S.P. (1996). Display-based problem solving strategies in computer programming. In W.D. Gray & D.A. Boehm-Davis (Eds.), *Empirical Studies of Programmers: Sixth Workshop*. Norwood, NJ: Ablex, pp. 59-76.

Davies, S.P & Castell, A.M. (1992). Doing design and describing it: accounting for divergent perspectives in software design. In *Proceedings 5th Workshop of the Psychology of Programming Interest Group*. INRIA., pp. 72-88.

De Beni, R., Moé, A & Cornoldi, C. (1997). Learning from texts or lectures: Loci mnemonics can interfere with reading but not with listening. *European Journal of Cognitive Psychology*, **9**(4), 401-415.

De Vega, M., Rodrigo, M.J. & Zimmer, H. (1996). Pointing and labelling directions in egocentric frameworks. *Journal of Memory and Language*, **35**(6), 821-839.

Deglin, V.L. & Kinsbourne, M. (1996). Divergent thinking styles of the hemispheres: How syllogisms are solved during transitory hemisphere suppression. *Brain and Cognition*, **31**(3), 285-307.

Delgado, A.R. & Prieto, G. (1996). Sex differences in visuospatial ability: Do performance factors play such an important role? *Memory & Cognition*, **24**(4), 504-510.

DeLoache, J.S. & Marzolf, D.P. (1992). When a picture is not worth a thousand words: Young children's understanding of pictures and models. *Cognitive Development*, **7**, 317-329.

Dennett, D.C. (1981). Two approaches to mental images. In N. Block (Ed.), *Imagery*. Cambridge, MA: MIT Press, pp. 87-107.

di Sessa, A.A. (1986). Notes on the future of programming: breaking the utility barrier. In D.A. Norman & S.W. Draper (Eds.), *User Centered System Design: New Perspectives on Human-Computer Interaction*. Hillsdale, NJ: Lawrence Erlbaum, pp. 125-152.

Diaz-Herrera, J.L. & Flude, R.C. (1980). PASCAL/HSD: a graphical programming system. In *Proceedings COMPSAC'80, Chicago, IEEE Computer Society Press*. pp. 723-728.

Dillon, L.K.. Kutty, G. Melliar-Smith, P.M., Moser L.E. & Ramakrishna, Y.S. (1994). Visual specifications for temporal reasoning. *Journal of Visual Languages and Computing*, **5**(1), 61-81.

Dix, A., Finlay, J., Abowd, G.L. & Beale, R. (1998). *Human computer interaction* (2nd ed.). Hemel Hempstead, UK: Prentice Hall.

Dondis, D.A. (1973). *A primer of visual literacy*. Cambridge, MA: MIT Press.

Dopkins, S. (1996). The role of imagery in the mental representation of negative sentences. *American Journal of Psychology*, **109**(4), 551-565.

Dreistadt, R. (1968). An analysis of the use of analogies and metaphors in science. *The Journal of Psychology*, **68**, 97-116.

Dreyfuss, H. (1972). *Symbol sourcebook*. New York: McGraw-Hill.

du Boulay, B., O'Shea, T. & Monk, J. (1981). The black box inside the glass box: Presenting computing concepts to novices. *International Journal of Man-Machine Studies*, **14**(3), 237-249.

Duisberg, R.A. (1988). Animation using temporal constraints: an overview of the animus system. *Human Computer Interaction*, **3**(3), 275-307.

Eberts, R.E. & Bittianda, K.P. (1993). Preferred mental models for direct manipulation and command-based interfaces. *International Journal of Man Machine Studies*, **38**(5), 769-786.

Edel, M. (1986). The Tinkertoy graphical programming environment. In *Proceedings COMPSAC'86, Chicago, IEEE Computer Society Press*. pp. 466-471.

Edwards, B. (1979). *Drawing on the right side of the brain*. Los Angeles: Tarcher.

Egan, D.E. & Schwartz, B.J. (1979). Chunking in recall of symbolic drawings. *Memory & Cognition*, **7**(2), 149-158.

Eisenberg, M., Resnick, M. & Turbak, F. (1987). Understanding procedures as objects. In G.M. Olson, S. Sheppard & E. Soloway (Eds.), *Empirical Studies of Programmers: Second Workshop*. Norwood, NJ: Ablex, pp. 14-32.

Eisenstadt, M., Breuker, J. & Evertsz, R. (1984). A cognitive account of 'natural' looping constructs. In B. Shackel (Ed.), *Human-Computer Interaction – Interact '84*. Amsterdam: Elsevier, pp. 455-460.

Ellington, H., Addinall, E. & Percival, F. (1982). *A handbook of game design*. London: Kogan Page.

Empson, W. (1984). *Seven types of ambiguity (3rd edition)*. London: Hogarth Press.

Ericsson, K.A. & Simon, H.A. (1993). *Protocol analysis: Verbal reports as data*. (revised ed.). Cambridge, MA: MIT Press.

Esteban, O., Chatty, S. & Palanque, P. (1995). Whizz'ed: A visual environment for building highly interactive software. In K. Nordby, P. Helmersen, D.J. Gilmore & S.A. Arnesen (Eds.), *Human Computer Interaction: Interact '95*. London: Chapman & Hall, pp. 121-126.

Fallside, D.C. & Just, M.A. (1994). Understanding the kinematics of a simple machine. *Visual Cognition*, **1**(4), 401-432.

Faltings, B. (1987). A theory of qualitative kinematics in mechanisms. In *Proceedings of the International Joint Conference on Artificial Intelligence*, pp. 436-442.

Farah,M.J., Hammond,K.M., Levine,D.N. & Calvanio,R. (1988). Visual and spatial mental imagery: Dissociable systems of representation. *Cognitive Psychology*, **20**, 439-462.

Faulkner, C. (1998). *The Essence of Human-Computer Interaction*. Hemel Hempstead, UK: Prentice Hall.

Fenson, L. (1985). The transition from construction to sketching in children's drawings. In N.H. Freeman & M.V. Cox (Eds.), *Visual order: The nature and development of pictorial representation*. Cambridge: Cambridge University Press, pp. 374-384.

Ferguson, E.S. (1992). *Engineering and the Mind's Eye*. Cambridge, MA: MIT Press.

Finke, R.A. (1996). Imagery, creativity, and emergent structure. *Consciousness and Cognition*, **5**(3), 381-393.

Finke, R.A., Pinker, S. & Farah, M.J. (1989). Reinterpreting visual patterns in mental imagery. *Cognitive Science*, **13**(1), 51-78.

Finke, R.A. & Slayton, K. (1988). Explorations of creative visual synthesis in mental imagery. *Memory & Cognition*, **16**(3), 252-257.

Finkel, R.A. (1996). *Advanced programming language design*. Menlo Park, CA: Addison-Wesley.

Fish, J. & Scrivener, S. (1990). Amplifying the mind's eye: Sketching and visual cognition. *Leonardo*, **23**(1), 117-126.

Fisher, C. (1987). Advancing the study of programming with computer-aided protocol analysis. In G.M. Olson, S. Sheppard & E. Soloway (Eds.), *Empirical Studies of Programmers: Second Workshop*. Norwood, NJ: Ablex, pp. 198-216.

Fitter, M. & Green, T.R.G. (1979). When do diagrams make good computer languages? *International Journal of Man-Machine Studies*, **11**(2), 235-261.

Flavell, J.H. (1979). Metacognition and cognitive monitoring. *American Psychologist*, **34**(10), 906-911.

Forbus, K.D. (1983). Qualitative reasoning about space and motion. In D. Gentner & A. Stevens (Eds.) *Mental Models*. Lawrence Erlbaum Associates, pp. 53-73.

Ford, L. (1993). *How programmers visualise programs*. (Report No. R.271). University of Exeter, Department of Computer Science. Available FTP: ftp://ftp.dcs.ex.ac.uk/pub/media/sv/esp.ps.Z

Ford, L. & Tallis, D. (1993). Interacting visual abstractions of programs. In *Proceedings IEEE Workshop on Visual Languages*.

Frandsen, A.N. & Holder, J.R. (1969). Spatial visualization in solving complex verbal problems. *The Journal of Psychology*, **73**, 229-233.

Fuchs, A., Goschke, T & Gude, D. (1988). On the role of imagery in linear syllogistic reasoning. *Psychological Research*, **50**, 43-49.

Gagné, R.M. & Smith, E.C. Jr. (1962). A study of the effects of verbalisation on problem-solving. *Journal of Experimental Psychology*, **63**(1), 12-18.

Galitz, W.O. (1997). *The essential guide to user interface design*. New York: Wiley.

Gallagher, J.M. (1978). The future of formal thought research: The study of analogy and metaphor. In B.Z. Presseisen, D. Goldstein & M.H. Appel (Eds.), *Topics in Cognitive Development, Volume 2: Language and Operational Thought*. New York: Plenum Press, pp. 77-98.

Gardin, F. & Meltzer, B. (1995). Analogical representations of naive physics. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 669-689.

Gattis, M. & Holyoak, K.J. (1996). Mapping conceptual to spatial relations in visual processing. *Journal of Experimental Psychology: Learning, Memory & Cognition*, **22**(1), 231-239.

Gentner, D. (1983). Structure-mapping: a theoretical framework for analogy. *Cognitive Science*, **7**(2), 155-170.

Gentner, D. & Clement, C. (1988). Evidence for relational selectivity in the interpretation of analogy and metaphor. In G.H. Bower (Ed.), *The Psychology of Learning and Motivation: Volume 22*. San Diego: Academic Press, pp. 307-358.

Gentner, D., Falkenhainer, B. & Skorstad, J. (1988). Viewing metaphor as analogy. In D.H. Helman (Ed.), *Analogical Reasoning: Perspectives of Artificial Intelligence, Cognitive Science and Philosophy*. Kluwer, pp. 171-177.

Gentner, D. & Wolff, P. (1997). Alignment in the processing of metaphor. *Journal of Memory and Language*, **37**(3), 331-355.

Gibbs, R.W. Jr. (1996). Why many concepts are metaphorical. *Cognition*, **61**(3), 195-324.

Gibbs, R.W. Jr. & O'Brien, J.E. (1990). Idioms and mental imagery: The metaphorical motivation for idiomatic meaning. *Cognition*, **36**(1), 35-68.

Gibson, J.J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.

Gick, M.L. & Holyoak, K.J. (1983). Schema induction and analogical transfer. *Cognitive Psychology*, **15**(1), 1-38.

Gillan, D.J. (1995). Visual arithmetic, computational graphics and the spatial metaphor. *Human Factors*, **37**(4), 766-780.

Gilmore, D.J. & Green, T.R.G. (1984a). Comprehension and recall of miniature programs. *International Journal of Man-Machine Studies*, **21**(1), 31-48.

Gilmore, D.J. & Green, T.R.G. (1984b). The comprehensibility of programming notations. In B. Shackel (Ed.), *Human-Computer Interaction – Interact '84*. Amsterdam: Elsevier, pp. 461-464.

Glasgow, J., Narayanan, N.H. & Chandrasekaran, B. (Eds.). (1995). *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press.

Glasgow, J.I. & Papadias, D. (1995). Computational imagery. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 435-480.

Glenberg, A.M. (1997). What memory is for. *Behavioral and Brain Sciences*, **20**(1), 1-55.

Glenberg, A.M., Langston, W.E. (1992). Comprehension of illustrated text: Pictures help to build mental models. *Journal of Memory and Language*, **31**, 129-151.

Glenberg, A.M., Wilkinson, A.C. & Epstein, W. (1982). The illusion of knowing: Failure in the self-assessment of comprehension. *Memory & Cognition*, **10**(6), 597-602.

Glinert, E.P. (1990). Nontextual programming environments. In S-K. Chang, (Ed.), *Principles of Visual Programming Systems*. Prentice-Hall, pp. 144-232.

Glinert, E.P. (Ed.). (1990a). *Visual programming environments: Applications and issues*. IEEE Computer Society Press.

Glinert, E.P. (Ed.). (1990b). *Visual programming environments: Paradigms and Systems*. IEEE Computer Society Press.

Glinert, E.P. & Gonczarowski, J. (1987). A (formal) model for (iconic) programming environments. In *Proceedings Interact '87*, Elsevier. pp. 283-290.

Glinert, E.P. & Tanimoto, S.L. (1984). Pict: an interactive graphical programming environment. *IEEE Computer*, 17(11), 7-25.

Glucksberg, S. & Keysar, B. (1993). How metaphors work. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 401-424.

Goel, V. (1992). 'Ill-structured representations' for ill-structured problems. *Proceedings 14th Annual Conference Cognitive Science Society* pp. 130-135.

Goel, V. (1995). *Sketches of thought*. Cambridge MA: MIT Press.

Goldberg, A., Burnett M. & Lewis, T. (1995). What is visual object-oriented programming? In M. Burnett, A. Goldberg & T. Lewis, (Eds.), *Visual Object-Oriented Programming Concepts and Environments*. Greenwich, CT: Manning, pp. 3-20.

Goldberg, E. & Costa, L.D. (1981). Hemisphere differences in the acquisition and use of descriptive systems. *Brain and Language*, **14**(1), 144-173.

Goldschmidt, G. (1991). The dialectics of sketching. *Creativity Research Journal*, **4**(2), 123-143.

Goldschmidt, G. (1994). On visual design thinking: The vis kids of architecture. *Design Studies*, **15**(2), 158-174.

Goldsmith, E. (1984). *Research into Illustration: An approach and a review*. Cambridge: Cambridge University Press.

Gombrich, E. (1990). Pictorial illustrations. In H. Barlow, C. Blakemore & M. Weston-Smith (Eds.), *Images and Understanding*. Cambridge: Cambridge University Press, pp. 26-45.

Good, Judith R. (1996). The 'right' tool for the task: an investigation of external representations, program abstractions and task requirements. In W.D. Gray & D.A. Boehm-Davis (Eds.), *Empirical Studies of Programmers: Sixth Workshop*. Norwood, NJ: Ablex, pp. 77-98.

Gooding, D. (1996). Diagrams in the generation and dissemination of new science: Some examples and applications. *Thinking with Diagrams*. Digest No. 96/010. London: IEE Computing and Control Division, pp. 3/1-3/6.

Goodman, N. (1969). *Languages of art: An approach to a theory of symbols*. London: Oxford University Press.

Goodman, N. (1990). Pictures in the mind? In H. Barlow, C. Blakemore & M. Weston-Smith (Eds.), *Images and Understanding*. Cambridge: Cambridge University Press, pp. 358-364.

Goolkasian, P. (1996). Picture-word differences in a sentence verification task. *Memory & Cognition*, **24**(5), 584-594.

Gordon, R.M. (1986). Folk psychology as simulation. *Mind and Language* 1(2), 158-171.

Grant, C. (in press). Visual language editing using a grammar-based structure editor. To appear in *Journal of Visual Languages and Computing.*

Green, A.J.K. & Barnard, P.J. (1990). Iconic interfacing: the role of icon distinctiveness and fixed or variable screen locations. In D. Diaper, D. Gilmore, G. Cockton & B. Shackel (Eds.), *Human-Computer Interaction – Interact '90*. Amsterdam: Elsevier, pp. 457-462.

Green, T.R.G. (1980). Programming as a cognitive activity. In H.T.Smith and T.R.G. Green (Eds.), *Human Interaction with Computers*. Academic Press, pp. 271-320.

Green, T.R.G. (1982). Pictures of programs and other processes, or how to do things with lines. *Behaviour and Information Technology*, **1**(1), 3-36.

Green, T.R.G. (1989). Cognitive dimensions of notations. In A. Sutcliffe & L. Macaulay (Eds.), *People and Computers V*. Cambridge University Press.

Green, T.R.G., Bellamy, R.K.E. & Parker, J.M. (1987). Parsing and gnisrap: A model of device use. In G.M. Olson, S. Sheppard & E. Soloway (Eds.), *Empirical Studies of Programmers: Second Workshop*. Norwood, NJ: Ablex, pp. 132-146.

Green, T.R.G. & Blackwell, A.F. (1996a). Thinking about visual programs. *Thinking with Diagrams*. Digest No. 96/010. London: IEE Computing and Control Division, pp. 5/1-5/4.

Green, T.R.G. & Blackwell, A.F. (1996b). *Ironies of Abstraction.* Paper presented at the Third International Conference on Thinking. British Psychological Society, London.

Green, T.R.G. & Navarro, R. (1995). Programming plans, imagery and visual programming. In *Proceedings Interact '95*, pp. 139-144.

Green, T.R.G. & Petre, M. (1992). When visual programs are harder to read than textual programs. In G.C. van der Veer & S. Bagnarola (Eds.), *Proceedings of ECCE-6 (European Conference on Cognitive Ergonomics).*

Green, T.R.G. & Petre, M. (1996). Usability analysis of visual programming environments: a 'cognitive dimensions' approach. *Journal of Visual Languages and Computing*, **7**,131-174.

Green, T.R.G., Petre, M. & Bellamy, R.K.E. (1991). Comprehensibility of visual and textual programs: A test of superlativism against the 'match-mismatch' conjecture. In J. Koenemann-Belliveau, T.G. Moher & S.P. Robertson (Eds.): *Empirical Studies of Programmers: Fourth Workshop* Norwood, NJ: Ablex, pp. 121-146.

Greeno, J.G. (1989). Situations, mental models, and generative knowledge. In D. Klahr & K. Kotovsky (Eds.), *Complex information processing: The impact of Herbert A. Simon*. Hillsdale, NJ: Lawrence Erlbaum Associates, pp. 285-318.

Gregory, R.L. (1970). *The Intelligent Eye*. London: Weidenfeld & Nicolson.

Grossberg, S. (1997). Cortical dynamics of three-dimensional figure-ground perception of two-dimensional pictures. *Psychological Review*, **104**(3), 618-658.

Gutfreund, S.H. (1987). Maniplicons in ThinkerToy. In *Proceedings OOPSLA 87, ACM Press*, pp. 307-317.

Hackos, J.T. & Redish, J.C. (1998). *User and Task Analysis for Interface Design*. New York: Wiley.

Halasz, F. & Moran, T.P. (1982). Analogy considered harmful. *Proceedings Conference Human Factors in Computer Systems*, pp. 383-386.

Halewood, K. & Woodward, M.R. (1993). A uniform graphical view of the program construction process: GRIPSE. *International Journal of Man Machine Studies*, **38**(5), 805-838.

Halpern, D.F. (1996). Sex, brains, hands, and spatial cognition. *Developmental Review*, **16**(3), 261-270.

Hayes, P.J. (1985) The second naive physics manifesto. In J.R Hobbs & R.C. Moore (Eds.), *Formal Theories of the Commonsense World*. Norwood, NJ: Ablex, pp. 1-36.

Hegarty, M. (1992). Mental animation: Inferring motion from static displays of mechanical systems. *Journal of Experimental Psychology: Learning, Memory & Cognition*, **18**(5), 1084-1102.

Hekkert, P. & van Wieringen, P.C.W. (1996). The impact of level of expertise on the evaluation of original and altered versions of post-impressionistic paintings. *Acta Psychologica*, **94**(2), 117-132.

Hesse, F.W., Kauer, G. & Spies, K. (1997). Effects of emotion-related surface similarity in analogical problem solving. *American Journal of Psychology*, **110**(3), 357-383.

Heydenbluth, C. & Hesse, F.W. (1996). Impact of superficial similarity in the application phase of analogical problem solving. *American Journal of Psychology*, **109**(1), 37-57.

Hill, S. (1995). *A practical introduction to the human computer interface in a semester*. London: DP Publications.

Hishitani, S. (1990). Imagery experts: How do expert abacus operators process imagery? *Applied Cognitive Psychology*, **4**(1), 33-46.

Hoffman, D.D. & Richards, W.A. (1984). Parts of recognition. *Cognition*, **18**, 65-96.

Holland, J.H., Holyoak, K.J., Nisbett, R.E. &Thagard, P.R. (1986). *Induction: Processes of inference, learning, and discovery*. MIT Press.

Hollands, J.G. & Spence, Ian. (1992). Judgements of change and proportion in graphical perception. *Human Factors*, **34**(3), 313-334.

Huang, K.-T. (1990). Visual interface design systems. In S.-K. Chang, (Ed.), *Principles of Visual Programming Systems*. Prentice-Hall, pp. 60-143.

Hutchins E. (1989). Metaphors for interface design. In M.Taylor, F.Neel & D.Bouwhuis (Eds.), *The Structure of Multimodal Dialogue*. Amsterdam, North-Holland: Elsevier, pp. 11-28.

Huttenlocher, J. (1968). Constructing spatial images: a strategy in reasoning. *Psychological Review*, **75**(6), 550-560.

Hyrskykari, A. (1993, March). *Development of program visualization systems*. Paper presented at the 2nd Czech British Symposium of Visual Aspects of Man-Machine Systems, Prague.

Ichikawa, T.& Hirakawa, M. (1987). Visual programming – toward realization of user-friendly programming environments. In *Proceedings 2nd Fall Joint Computer Conference, IEEE Computer Society Press*, pp. 129-137.

Ittelson, W.H. (1996). Visual perception of markings. *Psychonomic Bulletin & Review*, **3**(2), 171-187.

Ivins, W.M. Jr. (1953). *Prints and visual communication*. London, Routledge & Kegan Paul.

Jackendoff, R. (1983). *Semantics and cognition*. Cambridge, MA: MIT Press.

Johnson, J., Roberts, T.L., Verplank, W., Smith, D.C., Irby, C.H., Beard, M. & Mackey, K. (1989). The Xerox Star: A retrospective. *IEEE Computer*, **22**(9), 11-26.

Johnson, M. (1987). *The body in the mind: The bodily basis of meaning, imagination and reason*. Chicago: University of Chicago Press.

Johnson, S.H. (1991). Adult age differences in visual mental imagery: Evidence for differentially age-sensitive components. *Proceedings 13th Annual Conference Cognitive Science Society* pp. 755–759.

Johnson-Laird, P.N. (1988). Freedom & constraint in creativity. In R.J. Sternberg (Ed.), *The nature of creativity: Contemporary psychological perspectives*. Cambridge: Cambridge, pp. 202-219.

Jones, A. (1984). How novices learn to program. In B. Shackel (Ed.), *Human Computer Interaction – INTERACT'84*. North Holland: Elsevier, pp. 777-783.

Jones, M.R. (1990). Mac-thusiasm: social aspects of microcomputer use. In D. Diaper, D. Gilmore, G. Cockton & B. Shackel (Eds.), *Human-Computer Interaction – Interact '90*. Amsterdam: Elsevier, pp. 21-26.

Kahn, K. (1996). Seeing systolic computations in a video game world. *Proceedings IEEE Symposium on Visual Languages*. Los Alamitos, CA: IEEE Computer Society Press, pp. 95-101.

Kaput, J.J. (1995). Overcoming physicality and the eternal present: cybernetic manipulatives. In R. Sutherland & J. Mason (Eds.), *Exploiting Mental Imagery with Computers in Mathematics Education*. Nato ASI Series F, Volume 138, pp. 161-177.

Karmiloff-Smith, A. (1990). Constraints on representational change: Evidence from children's drawing. *Cognition*, **34**(1), 57-83.

Karsai, G. (1995). A configurable visual programming environment: a tool for domain-specific programming. *IEEE Computer*, **28**(3), 36-44.

Katona, G. (1940). *Organizing and Memorizing*. New York: Columbia University Press.

Katz, A.N. (1983). What does it mean to be a high imager? In J.C. Yuille (Ed.), *Imagery, Memory and Cognition: Essays in honor of Allan Paivio*. Hillsdale, NJ: Erlbaum, pp. 39-63.

Kaufmann, G. (1979). *Visual imagery and its relation to problem solving*. Oslo, Norway: Universitetsforlaget.

Keane, M.T. (1988). *Analogical problem solving*. Ellis Horwood Ltd.

Keane, M.T. (1997). What makes an analogy difficult? The effects of order and causal structure on analogical mapping. *Journal of Experimental Psychology: Learning, Memory and Cognition*, **23**(4), 946-967.

Kearins, J.M. (1981). Visual spatial memory in Australian Aboriginal children of desert regions. *Cognitive Psychology*, **13**, 434-460.

Kennedy, J.M. (1975). Drawing was discovered, not invented. *New Scientist*, **67**(965), 523-525.

Kennedy, J.M., Green, C.D. & Vervaeke, J. (1993). Metaphoric thought and devices in pictures. *Metaphor and symbolic activity*, **8**(3), 243-255.

Kieras, D. (1978). Beyond pictures and words: alternative information-processing models for imagery effects in verbal memory. *Psychological Bulletin*, **85**(3), 532-554.

Kieras, D.E. & Bovair, S. (1984). The role of a mental model in learning to operate a device. *Cognitive Science*, **8**(3), 255-273.

Kimura, T.D., Apte, A., Sengupta S. & Chan, J.W. (1995). Form/Formula: A visual programming paradigm for user-definable user interfaces. *IEEE Computer*, **28**(3), 27-35.

Koedinger, K.R & Anderson, J.R. (1990). Abstract planning and perceptual chunks: elements of expertise in geometry. *Cognitive Science*, **14**(4), 511-550.

Koenemann, J. & Robertson, S.P. (1991). Expert problem solving strategies for program comprehension. In Robertson, S.P., Olson, G.M. & Olson, J.S. (Eds.), *Proceedings CHI'91*. ACM, pp. 125-130.

Koestler, A. (1964). *The act of creation*. London: Hutchinson.

Kopache, M.E. & Glinert, E.P. (1988). C2: A mixed textual/graphical environment for C. In *Proceedings IEEE Workshop on Visual Languages*, pp. 231-238.

Kosslyn, S.M. (1981). The medium and the message in mental imagery: a theory. *Psychological Review*, **88**(1), 46-66.

Kosslyn, S.M. (1989). Understanding charts and graphs. *Applied Cognitive Psychology*, **3**(3), 185-226.

Kosslyn, S.M., Ball, T.M. & Reiser, B.J. (1978). Visual images preserve metric spatial information: Evidence from studies of image scanning. Journal of Experimental Psychology: Human Perception and Performance, **4**, 47-60.

Kosslyn, S.M., Koenig, O., Barrett, A., Cave, C.B., Tang, J., & Gabrieli, J.D.E. (1989). Evidence for two types of spatial representations: hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception and Performance*, **15**(4), 723-735.

Labbo, L.D. (1996). A semiotic analysis of young children's symbol making in a classroom computer centre. *Reading Research Quarterly*, **31**(4), 356-385.

Ladret, D. & Rueher, M. (1991). VLP: A visual logic programming language. *Journal of Visual Languages and Computing*, **2**(2) , 163-188.

Lakoff, G. (1987). *Women, fire and dangerous things*. Chicago: University of Chicago Press.

Lakoff, G. (1993). The contemporary theory of metaphor. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 202-251.

Lakoff, G. & Johnson, M. (1980). *Metaphors We Live By*. Chicago, The University of Chicago Press.

Langston, W., Kramer, D.C. & Glenberg, A.M. (1998). The representation of space in mental models derived from text. *Memory & Cognition*, **26**(2), 247-262.

Larkin, J.H. (1989). Display-based problem solving. In D. Klahr & K. Kotovsky (Eds.), *Complex Information Processing: The impact of Herbert A. Simon*. Hillsdale, NJ: Lawrence Erlbaum Associates, pp. 319-342.

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

Laurel, B. (1986). Interface as mimesis. In D.A. Norman & S.W. Draper (Eds.), *User Centered System Design: New Perspectives on Human-Computer Interaction*. Hillsdale, NJ: Lawrence Erlbaum, pp. 67-86.

Lave, J. (1988). *Cognition in Practice: Mind, mathematics and culture in everyday life*. Cambridge, UK: Cambridge University Press.

Levelt, W.J.M. (1981). The speaker's linearisation problem. *Philosophical Transactions of the Royal Society B*, **295**, 305-315.

Lewis, C.M. (1991). Visualization and situations. In J. Barwise, J.M. Gawron, G. Plotkin & S. Tutiya (Eds.), *Situation Theory and Its Applications: Volume 2*. Stanford University: CSLI, pp. 553-580.

Linde, C. & Labov, W. (1975). Spatial structures as a site for the study of language and thought. *Language*, **51**, 924-939.

Lindsay, R.K. (1988). Images and inference. *Cognition*, **29**(3), 229-250.

Lindsay, R.K. (1989). Qualitative geometric reasoning. *Proceedings 11th Annual Conference Cognitive Science Society* pp. 418-425.

Liu, C.H. & Kennedy, J.M. (1994). Symbolic forms can be mnemonics for recall. *Psychonomic Bulletin & Review*, **1**(4), 494-498.

Lodding, K.N. (1983). Iconic interfacing. *IEEE Computer Graphics and Applications*, **3**(2), 11-20.

Logie, R.H. & Pearson, D.G. (1997). The inner eye and the inner scribe of visuo-spatial working memory: Evidence from developmental fractionation. *European Journal of Cognitive Psychology*, **9**(3), 241-257.

Lohse, G.L. (1997). The role of working memory on graphical information processing. *Behaviour and Information Technology*, **16**(6), 297-308.

Lohse, G.L., Biolski, K., Walker, N. & Rueter, H.H. (1994). A classification of visual representations. *Communications of the ACM*, **37**(12), 36-49.

Lord, H.D. (1994). Visual programming for visual applications: a new look for computing. *Object Magazine*, **4**(4), 37-40.

Lowe, R.K. (1993a). *Successful instructional diagrams*. London: Kogan Page.

Lowe, R.K. (1993b). Diagrammatic information: techniques for exploring its mental representation and processing. *Information Design Journal*, **7**(1), 3-18.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A.L. Stevens (Eds.), *Mental Models*. Lawrence Erlbaum Associates, pp. 299-324.

McDougal, T.F. & Hammond, K.J. (1995). Using diagrammatic features to index plans for geometry theorem-proving. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 691-709.

McGlone, M.S. (1996). Conceptual metaphors and figurative language interpretation: Food for thought? *Journal of Memory and Language*, **35**(4), 544-565.

MacGregor, J.N. & Ormerod, T. (1996). Human performance on the travelling salesman problem. *Perception and Psychophysics*, **58**(4), 527-539.

McKeithen, K.B., Reitman, J.S., Rueter, H.H. & Hirtle, S.C. (1981). Knowledge organization and skill differences in computer programmers. *Cognitive Psychology*, **13**, 307-325.

MacLeod, C.M., Hunt, E.B. & Mathews, N.N. (1978). Individual differences in the verification of sentence-picture relationships. *Journal of Verbal Learning and Verbal Behavior*, **17**, 493-507.

McNamara, T.P. (1986). Mental representations of spatial relations. *Cognitive Psychology*, **18**, 87-121.

McNamara, T.P., Halpin, J.A. & Hardy, J.K. (1992). The representation and integration in memory of spatial and nonspatial information. *Memory & Cognition*, **20**(5), 519-532.

Madsen, K.H. (1994). A guide to metaphorical design. *Communications of the ACM*, **37**(12), 57-62.

Mandel, T. (1997). *The elements of user interface design*. New York: Wiley.

Manger, T. & Eikeland, O.-J. (1998). The effects of spatial visualization and students' sex on mathematical achievement. *British Journal of Psychology*, **89**(1), 17-25.

Mani, K. & Johnson-Laird, P.N. (1982). The mental representations of spatial descriptions. *Memory & Cognition*, **10**(2), 181-187.

Marschark, M. & Hunt, R.R. (1985). On memory for metaphor. *Memory & Cognition*, **13**(5), 413-424.

Martin, J. & McClure, C. (1985). *Diagramming techniques for analysts and programmers*. Englewood Cliffs, NJ: Prentice-Hall.

Martin, M. & Jones, G.V. (1998). Generalizing everyday memory: Signs and handedness. *Memory & Cognition*, **26**(2), 193-200.

Matsuno, T. (1987). Cognitive style and representational strategies in categorical syllogistic reasoning. *Tohoku Psychologica Folia*, **46**(1-4), 97-102.

Mayer, R.E. & Sims, V.K. (1994). For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning. *Journal of Educational Psychology*, **86**(3), 389-401.

Mayer, R.E. (1975). Different problem-solving competencies established in learning computer programming with and without meaningful models. *Journal of Educational Psychology*, **67**(6), 725-734.

Mayer, R.E. (1988). From novice to expert. In M. Helander (Ed.), *Handbook of Human-Computer Interaction*. Elsevier, pp. 569-580.

Mayer, R.E. (1993). The instructive metaphor: Metaphoric aids to student's understanding of science. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 562-578.

Mecklinger, A. & Müller, N. (1996). Dissociations in the processing of "what" and "where" information in working memory: An event-related potential analysis. *Journal of Cognitive Neuroscience*, **8**(5), 453-473.

Melcher, J.M. & Schooler, J.W. (1996). The misremembrance of wines past: Verbal and perceptual expertise differentially mediate verbal overshadowing of taste memory. *Journal of Memory and Language*, **35**(2), 231-245.

Mendelsohn, P., Green, T.R.G. & Brna, P. (1990). Programming languages in education: The search for an easy start. In Hoc, J.-M., Green, T.R.G., Samurçay, R. & Gilmore, D.J. (Eds.), *Psychology of programming*. London: Academic Press, pp. 175-200.

Metcalfe, J. & Wiebe, D. (1987). Intuition in insight and noninsight problem solving. *Memory & Cognition*, **15**(3), 238-246.

Meyer, J. (1997). A new look at an old study on information display: Washburne (1927) reconsidered. *Human Factors*, **39**(3), 333-340.

Microsoft Corporation (1995). *The Windows interface guidelines for software design*. Redmond, WA: Author.

Mieder, W. (1990). "A picture is worth a thousand words": From advertising slogan to American proverb. *Southern Folklore*, **47**, 207-225.

Miller, George A. (1993). Images and models, similes and metaphors. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 357-400.

Mishkin, M., Ungerleider, L.G. & Macko, K.A. (1983). Object vision and spatial vision: Two cortical pathways. *Trends in Neurosciences*, **6**(10), 414-417.

Missikoff, M. & Pizzicanella, R. (1996). A visual approach to object-oriented analysis based on abstract diagrams. *SIGCHI Bulletin*, **28**(3), 56-64.

Mitchell, M. (1993). *Analogy-making as perception: A computer model*. Cambridge, MA: MIT Press.

Mohnkern, K. (1997a). *Affordances, metaphor and interface design*. Unpublished Master's thesis, Department of Design, College of Fine Arts, Carnegie Mellon University.

Mohnkern, K. (1997b). Beyond the interface metaphor. *SIGCHI Bulletin*, **29**(2), 11-15.

Moray, N. (1990). A lattice theory approach to the study of mental models. *Philosophical Transactions of the Royal Society B*, **327**, 577-583.

Murphy, G.L. (1996). On metaphoric representation. *Cognition*, **60**(2), 173-204.

Murphy, G.L. (1997). Reasons to doubt the present evidence for metaphoric representation. *Cognition*, **62**(1), 99-108.

Myers, B.A. (1986). Visual programming, programming by example, and program visualization: A taxonomy. *Proceedings CHI 86*, pp. 59-66.

Narayanan, N.H., Suwa, M. & Motoda, H. (1995). Hypothesising behaviors from device diagrams. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 501-534.

Nardi, B.A. (1993). *A small matter of programming: Perspectives on end user computing*. Cambridge, MA: MIT Press.

Nardi, B.A. & Zarmer, C.L. (1993). Beyond models and metaphors: visual formalisms in user interface design. *Journal of Visual Languages and Computing*, **4**(1), 5-33.

Nelson, T.O., Metzler, J. & Reed, D.A. (1974). Role of details in the long-term recognition of pictures and verbal descriptions. *Journal of Experimental Psychology*, **102**(1), 184-186.

Nersessian, N.J. (1995). Capturing the dynamics of conceptual change in science. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 137-181.

Netz, R. (in press). *The shaping of deduction in Greek mathematics*. Cambridge: Cambridge University Press.

Newsham, R. (1995). *Symbolic representation in object-oriented methodologies: Modelling the essence of the computer system*. Unpublished Master's thesis, Department of Computer Science, Nottingham Trent University.

Noble, R. (1992). Preferential use of examples by novices learning Prolog. In *Proceedings 5th Workshop of the Psychology of Programming Interest Group*. INRIA, pp. 146-158.

Nolder, R. (1991). Mixing metaphor and mathematics in the secondary classroom. In K. Durkin & B. Shire (Eds.), *Language in Mathematical Education: Research and Practice*. Buckingham, UK: Open University Press. pp. 105-114.

Norman, D.A. (1988). *The psychology of everyday things*. New York, Basic Books.

Norman, D.A. (1991). Cognitive artifacts. In J.M. Carroll (Ed.), *Designing Interaction: Psychology at the Human-Computer Interface*. Cambridge: Cambridge University Press, pp. 17-38.

Novak, G.S. Jr. (1995). Diagrams for solving physical problems. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 753-774.

Oberlander, J. (1996). Grice for graphics: pragmatic implicature in network diagrams. *Information Design Journal* , **8**(6), 163-179.

Paivio, A. (1971). *Imagery and Verbal Processes*. New York, Holt, Rinehart and Winston.

Paivio, A. (1983). The empirical case for dual coding. In J.C. Yuille (Ed.), *Imagery, Memory & Cognition: Essays in honor of Allan Paivio*. Hillsdale, NJ: Erlbaum, pp. 307-332.

Paivio, A. & Clark, J.M. (1991). Static versus dynamic imagery. In C. Cornoldi & M.A. McDaniel (Eds.), *Imagery and Cognition*. New York, Springer-Verlag, pp. 221-245.

Palmer, S. & Rock, I. (1994). Rethinking perceptual organization: the role of unifom connectedness. *Psychonomic Bulletin & Review*, **1**(1), 29-55.

Pane, J. (1997). A programming system for children that is designed for usability. In C. Kann (Ed.), *Proceedings of the First ESP Student Workshop*, pp. 15-22.

Pane, J.F. & Myers, B.A. (1996). *Usability issues in the design of novice programming systems*. School of Computer Science, Carnegie Mellon University. Technical Report CMU-CS-96-132.

Payne, S.J. (1988). Metaphorical instruction and the early learning of an abbreviated-command computer system. *Acta Psychologica*, **69**, 207-230.

Payne, S.J. (1990). Looking HCI in the I. In D. Diaper, D. Gilmore, G. Cockton & B. Shackel (Eds.), *Human-Computer Interaction – Interact '90*. Amsterdam: Elsevier, pp. 185-191.

Payne, S.J. (1991). A descriptive study of mental models. *Behaviour and Information Technology*, **10**(1), 3-21.

Payne, S.J. (1992). On mental models and cognitive artefacts. In Y. Rogers, A. Rutherford & P.A. Bibby (Eds.), *Models in the Mind: Theory, Perspective and Application*. Academic Press, pp. 103-118.

Payne, S.J., Squibb, H.R. & Howes, A. (1990). The nature of device models: the yoked state space hypothesis and some experiments with text editors. *Human-Computer Interaction*, **5**(4), 415-444.

Peirce, C.S. (1932). Elements of Logic. In Hartshorne, C. & Weiss, P. (Eds.), *Collected papers of Charles Sanders Peirce, Volume II*. Cambridge, MA: Harvard University Press.

Petre, M. & Blackwell, A.F. (1997). A glimpse of expert programmer's mental imagery. In S. Wiedenbeck & J. Scholtz (Eds.), *Proceedings of the 7th Workshop on Empirical Studies of Programmers*, pp. 109-123.

Petre, M. Blackwell, A.F. and Green, T.R.G. (1998). Cognitive questions in software visualisation. In J. Stasko, J. Domingue, M. Brown, and B. Price (Eds.) *Software Visualization: Programming as a Multi-Media Experience*. Cambridge, MA: MIT Press, pp. 453-480.

Petre, M. & Green, T.R.G. (1990). Where to draw the line with text: some claims by logic designers about graphics in notation. In D. Diaper, D. Gilmore, G. Cockton & B. Shackel (Eds.), *Human-Computer Interaction – Interact '90*. Amsterdam: Elsevier, pp. 463-468.

Petre, M. & Green, T.R.G. (1993). Learning to read graphics: some evidence that 'seeing' an information display is an acquired skill. *Journal of Visual Languages and Computing*, **4**(1), 5-33.

Petrie, H.G. & Oshlag, R.S. (1993). Metaphor and learning. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 579-609.

Pickford, R.W. (1979). Semantic differential judgements of geometric figures of aesthetic interest. In Nodine,C.F. & Fisher, D.F. (Eds.), *Perception and Pictorial Representation*. New York: Praeger, pp. 316-327.

Pilton, B. (1971). The intelligent ball bearing. *Manifold-9.* Mathematics Institute, University of Warwick, pp. 17-20.

Pimm, D. (1995). *Symbols and meanings in school mathematics*. London, Routledge.

Pinkpank, T. & Wandke, H. (1995). Mental effort with the use of different dialogue techniques in human-computer interaction. *Zeitschrift für Psychologie*, **203**, 119-137.

Pisan, Y. (1995). A visual routines based model of graph understanding. *Proceedings 17th Annual Conference Cognitive Science Society* pp. 692-697.

Pong, M.C. & Ng, N. (1983). PIGS – A system for programming with interactive graphical support. *Software – Practice and Experience*, **13**, 847-855.

Porter, T. (1979). *How architects visualize*. London: Studio Vista.

Potosnak, K. (1988). Do icons make user interfaces easier to use? *IEEE Software*, May, pp. 97-99.

Potter, M.C. & Faulconer, B.A. (1975). Time to understand pictures and words. *Nature*, **253**, 437-438.

Potter, M.C., Kroll, J.F, Yachzel, B., Carpenter, E. & Sherman, J. (1986). Pictures in sentences: understanding without words. *Journal of Experimental Psychology: General*, **115**(3), 281-294.

Price, B.A., Baecker, R.M. & Small, I.S. (1993). A principled taxonomy of software visualization. *Journal of Visual Languages and Computing*, **4**(3), 211-266.

Pylyshyn, Z.W. (1981). The imagery debate: analogue media versus tacit knowledge. *Psychological Review*, **88**(1), 16-45.

Pynte, J., Besson, M., Robichon, F.-H. & Poli, J. (1996). The time-course of metaphor comprehension: An event-related potential study. *Brain and Language*, **55**(3), 293-316.

Qin, Y. & Simon, H. (1995). Imagery and mental models. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 403-434.

Quinn, J.G. & McConnell, J. (1996). Irrelevant pictures in visual working memory. *The Quarterly Journal of Experimental Psychology*, **49A**, 200-215.

Reddy, M.J. (1993). The conduit metaphor: A case of frame conflict in our language about language. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 164-201.

Reiss, S.P. (1987). Visual languages and the GARDEN system. In P. Gorny & M.J. Tauber (Eds.), *Visualization in Programming*. Lecture Notes in Computer Science Vol. 282. Berlin: Springer-Verlag. pp. 178-191.

Repenning, A. & Sumner, T. (1995). Agentsheets: A medium for creating domain-oriented visual languages. *IEEE Computer*, 28(3), 17-25.

Richards, C. (1997). *Getting the picture: Diagram design and the information revolution*. Professorial Lectures:16; Coventry University.

Richardson, A. (1977). Verbalizer-visualizer: A cognitive style dimension. *Journal of Mental Imagery*, **1**, 109-126.

Riding, R. & Douglas, G. (1993). The effect of cognitive style and mode of presentation on learning performance. *British Journal of Educational Psychology*, **63**, 297-307.

Rieman, J., Lewis, C. Young, R.M. & Polson, P. (1994). Why is a raven like a writing desk? Lessons in interface consistency and analogical reasoning from two cognitive architectures. *Proceedings Human Factors in Computing Systems CHI 94*, pp. 438-444.

Rohr, G. (1987). How people comprehend unknown system structures: Conceptual primitives in systems' surface representations. In P. Gorny & M.J. Tauber (Eds.), *Visualization in Programming*. Lecture Notes in Computer Science Vol. 282. Berlin: Springer-Verlag, pp. 89-105.

Roszak, T. (1986). *The cult of information: The folklore of computers and the true art of thinking*. London: Paladin Press.

Rumelhart, D.E. (1993). Some problems with the notion of literal meanings. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 71-82.

Ryan, T.A. & Schwartz, C.B. (1956). Speed of perception as a function of mode of representation. *American Journal of Psychology*, **69**, 60-69.

Saariluoma, P. & Kalakoski, V. (1997). Skilled imagery and long-term working memory. *American Journal of Psychology*, **110**(2), 177-202.

Saariluoma, P. & Sajaniemi, J. (1994). Transforming verbal descriptions into mathematical formulas in spreadsheet calculation. *International Journal of Human Computer Studies*, **41**(6), 915-948.

Scaife, M. & Rogers, Y. (1996). External cognition: how do graphical representations work? *International Journal of Human Computer Studies*, **45**, 185-214.

Scapin, D.L. (1981). Computer commands in restricted natural language: some aspects of memory and experience. *Human Factors*, **23**(3), 365-375.

Schiffer, S. & Fröhlich, J.H. (1995). Visual programming and software engineering with Vista. In M. Burnett, A. Goldberg & T. Lewis, (Eds.), *Visual Object-Oriented Programming Concepts and Environments*. Greenwich, CT: Manning, pp. 199-228.

Schoenfeld, A.H. (1983). Beyond the purely cognitive: Belief systems, social cognitions and metacognitions as driving forces in intellectual performance. *Cognitive Science*, **7**(4), 329-363.

Scholtz, J. & Wiedenbeck, S. (1992). The role of planning in learning a new programming language. *International Journal of Man Machine Studies*, **37**(2), 191-214.

Schooler, J.W., Ohlsson, S. & Brooks, K. (1993). Thoughts beyond words: When language overshadows insight. *Journal of Experimental Psychology: General*, **122**(2), 166-183.

Schunn, C.D. & Dunbar, K. (1996). Priming, analogy and awareness in complex reasoning. *Memory & Cognition*, **24**(3), 271-284.

Schwartz, D.L. (1995). Reasoning about the referent of a picture versus reasoning about the picture as the referent: An effect of visual realism. *Memory & Cognition*, **23**(6), 709-722.

Schwartz, D.L. & Black, J.B. (1996a). Analog imagery in mental model reasoning: Depictive models. *Cognitive Psychology*, **30**(2), 154-219.

Schwartz, D.L. & Black, J.B. (1996b). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science*, **20**(4), 457-497.

Schwartz, R. (1981). Imagery – There's more to it than meets the eye. In N. Block (Ed.), *Imagery*. Cambridge, MA: MIT Press, pp. 109-130.

Schwartz, S.J. (1971). Modes of representation and problem solving: Well evolved is half solved. *Journal of Experimental Psychology*, **91**(2), 347-350.

Schweiker, H. & Muthig, K.-P. (1987). Solving interpolation problems with LOGO and BOXER. In P. Gorny & M.J. Tauber (Eds.), *Visualization in Programming*. Lecture Notes in Computer Science Vol. 282. Berlin: Springer-Verlag. pp. 164-177.

Scott, F.J. & Baron-Cohen, S. (1996). Imagining real and unreal things: Evidence of a dissociation in autism. *Journal of Cognitive Neuroscience*, **8**(4), 371-382.

Segal, J. & Schuman, S. (1992). Empirical studies of learners of functional programming. In *Proceedings Fifth Workshop of the Psychology of Programming Interest Group*. INRIA., pp. 197-206.

Sein, M.K., Olfman, L., Bostrom, R.P. & Davis, S.A. (1993). Visualization ability as a predictor of user learning success. *International Journal of Man-Machine Studies*, **39**, 599-620.

Selfe, L. (1985). Anomalous drawing development: Some clinical studies. In N.H. Freeman & M.V. Cox (Eds.), *Visual order: The nature and development of pictorial representation*. Cambridge: Cambridge University Press, pp. 135-154.

Shah, P. & Carpenter, P.A. (1995). Conceptual limitations in comprehending line graphs. *Journal of Experimental Psychology: General*, **124**(1), 43-61.

Shalit, A. & Boonzaier, D.A. (1990). HyperBliss: A Blissymbolics communication enhancement interface and teaching aid based on a cognitive semantographic technique with adaptive-predictive capability. In D. Diaper, D. Gilmore, G. Cockton & B. Shackel (Eds.), *Human-Computer Interaction – Interact '90*. Amsterdam: Elsevier, pp. 499-503.

Shaver, P., Pierson, L. & Lang, S. (1974/75). Converging evidence for the functional significance of imagery in problem solving. *Cognition*, **3**(4), 359-375.

Shepard, R.N. (1978). Externalization of mental images and the act of creation. In B.S. Randhawa & W.E. Coffman (Eds.), *Visual Learning, Thinking and Communication*. New York, Academic Press, pp. 133-189.

Shepard, R.N. & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, **171**, 701-703.

Shimaya, A. (1997). Perception of complex line drawings. *Journal of Experimental Psychology: Human Perception and Performance*, **23**(1), 25-50.

Shin, S.-J. (1991). A situation-theoretic account of valid reasoning with Venn diagrams. In J. Barwise, J.M. Gawron, G. Plotkin & S. Tutiya (Eds.), *Situation Theory and Its Applications: Volume 2*. Stanford University: CSLI, pp. 581-605.

Shneiderman, B. (1983). Direct manipulation: A step beyond programming languages. *IEEE Computer*, August, pp. 57-69.

Shu, N.C. (1986). Visual programming languages: A perspective and a dimensional analysis. In S.K. Chang, T. Ichikawa & P.A. Ligomenides, (Eds.), *Visual Languages*. Plenum, pp. 11-34.

Shu, N.C. (1988a). A visual programming environment for automatic programming. In *Proceedings 21st Hawaii International Conference on System Sciences*, IEEE Computer Society Press, pp. 662-671.

Shu, N.C. (1988b). *Visual programming*. New York: Van Nostrand Reinhold.

Silverman, I., Phillips, K. & Silverman, L.K. (1996). Homogeneity of effect sizes for sex across spatial tests and cultures: Implications for hormonal theories. *Brain and Cognition*, **31**(1), 90-94.

Simos, M. & Blackwell, A.F. (1998). Pruning the tree of trees: The evaluation of notations for domain modeling. In J. Domingue & P. Mulholland (Eds.), *Proceedings of the Tenth Annual Meeting of the Psychology of Programming Interest Group*, pp. 92-99.

Simpson, H.K. & Pellegrino, J.W. (1993). Descriptive models in learning command languages. *Journal of Educational Psychology*, **85**(3), 539-550.

Sims, V.K. & Hegarty, M. (1997). Mental animation in the visuospatial sketchpad: Evidence from dual-task studies. *Memory & Cognition*, **25**(3), 321-332.

Slezak, P. (1992). When can visual images be re-interpreted? Non-chronometric tests of pictorialism. In *Proceedings 14th Annual Conference of the Cognitive Science Society*, pp. 124-129.

Sloman, A. (1995). Musings on the roles of logical and nonlogical representations in intelligence. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 7-32.

Smith, D.C. (1977). *PYGMALION: A computer program to model and stimulate creative thinking*. Birkhäuser.

Smith, D.C. (1996). Making computers accessible to people. Contribution to panel on "Perspectives from the Pioneers", In *Proceedings 1996 IEEE Symposium on Visual Languages*. IEEE Computer Society Press, pp. 332-333.

Smith, D.C., Irby, C., Kimball, R. & Harslem, E. (1982). The Star user interface: An overview. In *Proceedings of the National Computer Conference, AFIPS Vol. 51*, pp. 515-528.

Smith, D.C., Irby, C., Kimball, R., Verplank, B. & Harslem, E. (1982). Designing the Star user interface. *Byte* **7**(4), 242-282.

Smith, E.E. & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive Psychology*, **33**(1), 5-42.

Smith, S.L. (1981). Exploring compatibility with words and pictures. *Human Factors*, **23**(3), 305-351.

Smyth, M., Anderson, B. & Alty, J.L. (1995). Metaphor reflections and a tool for thought. In M.A.R. Kirby, A.J. Dix & J.E. Finlay (Eds.), *People and Computers X*. Cambridge University Press, pp. 137-150.

Snyder, A.W. & Thomas, M. (1997). Autistic artists give clues to cognition. *Perception*, **26**(1), 93-96.

Sohn, Y.W. & Doane, S.M. (1997). Cognitive constraints on computer problem-solving skills. *Journal of Experimental Psychology: Applied*, **3**(4), 288-312.

Soloway, E., Bonar, J & Ehrlich, K. (1983). Cognitive strategies and looping constructs: An empirical study. *Communications of the ACM*, **26**(11), 853-860.

Sowa, J.F. (1993). Relating diagrams to logic. In G. Mineau, B. Moulin & J.F. Sowa (Eds.), *Conceptual Graphs for Knowledge Representation*. Berlin: Springer-Verlag, pp. 1-35.

Spence, I. (1990). Visual Psychophysics of simple graphical elements. *Journal of Experimental Psychology: Human Perception and Performance*, **16**(4), 683-692.

Spiro, R.J., Feltovich, P.J., Coulson, R.L & Anderson, D.K. (1989). Multiple analogies for complex concepts: antidotes for analogy-induced misconception in advanced knowledge acquisition. In S. Vosniadou & A. Ortony (Eds.), *Similarity and Analogical Reasoning*. Cambridge University Press, pp. 498-531.

Stenning, K. & Gurr, C. (1997). Human-formalism interaction: Studies in communication through formalism. *Interacting with Computers*, **9**(2), 111-128.

Stenning, K., Inder, R. & Neilson, I. (1995). Applying semantic concepts to analysing media and modalities. In B. Chandrasekaran, J. Glasgow & H. Narayanan (Eds.), *Diagrammatic Reasoning: Computational and Cognitive Perspectives on Problem Solving with Diagrams*. Menlo Park, CA: AAAI Press / MIT Press, pp. 303-338.

Stenning, K. & Oberlander, J. (1991). Reasoning with words, pictures and calculi: computation versus justification. In J. Barwise, J.M. Gawron, G. Plotkin & S. Tutiya (Eds.), *Situation Theory and Its Applications: Volume 2*. Stanford University: CSLI, pp. 607-621.

Stenning, K. & Oberlander, J. (1995). A cognitive theory of graphical and linguistic reasoning: Logic and implementation. *Cognitive Science*, **19**(1), 97-140.

Stone, E.R. & Yates, J.F. (1997). Effects of numerical and graphical displays on professed risk-taking behaviour. *Journal of Experimental Psychology: Applied*, **3**(4), 243-256.

Stroebel, L., Todd, H. & Zakia, R. (1980). *Visual concepts for photographers*. London: Focal Press.

Strothotte, C. & Strothotte, T. (1997). *Seeing between the pixels: Pictures in interactive systems*. Springer Verlag.

Sutcliffe, A. & Patel, U. (1996). 3D or not 3D: Is it nobler in the mind? In M.A. Sasse, R.J. Cunningham & R.L. Winder (Eds.), *People and computers XI: Proceedings of HCI'96*. London: Springer-Verlag, pp. 79-94.

Sutherland, I.E. (1963). Sketchpad: A man-machine graphical communication system. *AFIPS Conference Proceedings, Spring Joint Conference*, pp. 2-19.

Suwa, M. & Tversky, B. (1997). What do architects and students perceive in their design sketches? A protocol analysis. *Design Studies*, **18**, 385-403.

Szlichcinski, K.P. (1979). Diagrams and illustrations as aids to problem solving. *Instructional Science*, **8**, 253-274.

Tabachnek-Schijf, H.J.M., Leonardo, A.M. & Simon,H.A. (1997). CaMeRa: A computational model of multiple representations. *Cognitive Science*, **21**(3), 305-350.

Takahashi, S. (1995). Aesthetic properties of pictorial perception. *Psychological Review*, **102**(4), 671-683.

Talmy, L. (1983). How language structures space. In H.L. Pick & L.P. Acredolo (Eds.), *Spatial orientation: Theory, research and application*. New York: Plenum Press, pp. 225-282.

Tanimoto, S.L. & Glinert, E.P. (1986). Designing iconic programming systems: representation and learnability. *Proceedings IEEE Workshop on Visual Languages*. IEEE Computer Society Press, pp. 54-60.

Tauber, M.J. (1987). On visual interfaces and their conceptual analysis. In P. Gorny & M.J. Tauber (Eds.), *Visualization in Programming*. Lecture Notes in Computer Science Vol. 282. Berlin: Springer-Verlag. pp. 106-123.

Taylor, H.A. & Tversky, B. (1996). Perspective in spatial descriptions. *Journal of Memory and Language*, **35**(3), 371-391.

Taylor, J. (1990). Analysing novices analysing Prolog: What stories do novices tell themselves about Prolog? *Instructional Science*, **19**, 283-309.

Tenenberg, J.D. (1996). Virtual machines and program comprehension. In P. Vanneste, K. Bertels, B. De Decker & J.-M. Jaques (Eds.), *Proceedings of the 8th Annual Workshop of the Psychology of Programming Interest Group*, pp. 60-82.

Theios, J. & Amrhein, P.C. (1989). Theoretical analysis of the cognitive processing of lexical and pictorial stimuli: reading, naming and visual and conceptual derivatives. *Psychological Review*, **96**(1), 5-24.

Thomas, G.V. & Silk, A.M.J. (1990). *An introduction to the psychology of children's drawings*. Hemel Hempstead: Harvester Wheatsheaf.

Tourangeau, R. & Sternberg, R.J. (1982). Understanding and appreciating metaphors. *Cognition*, **11**(3), 203-244.

Treglown, M. (1994). Qualitative models of user interfaces. In G. Cockton, S.W. Draper & G.R.S. Weir (Eds.), *People and computers IX: Proceedings of HCI'94*. London: Springer-Verlag, pp. 261-272.

Tresch, M.C., Sinnamon, H.M. & Seamon, J.G. (1993). Double dissociation of spatial and object visual memory: Evidence from selective interference in intact human subjects. *Neuropsychologia*, **31**(3), 211-219.

Tripp, L.L. (1988). A survey of graphical notations for program design – an update. *Software Engineering Notes*, **13**(4), 39-44.

Tufte, E.R. (1983). *The visual display of quantitative information*. Cheshit, CT: Graphics Press.

Tufte, E.R. (1990). *Envisioning information*. Cheshit, CT: Graphics Press.

Tversky, B., Kugelmass, S. & Winter, A. (1991). Cross-cultural and developmental trends in graphic productions. *Cognitive Psychology*, **23**, 515-557.

Twyman, M. (1979). A schema for the study of graphical language. In P.A. Kolers, M.E. Wrolstad, & H. Bouma (Eds.), *Processing of Visible Language, Vol. 1*. New York: Plenum Press, pp. 117-150.

Ullman, S. (1984). Visual routines. *Cognition*, **18**, 97-159.

van der Veer, G.C. (1990). *Human-Computer Interaction: Learning, Individual Differences and Design Recommendations*. PhD Thesis, Free University of Amsterdam.

van der Veer, G.C., van Beek, J. & Cruts, G.A.N. (1987). Learning structured diagrams – effect of mathematical background, instruction and problem solving. In P. Gorny & M.J. Tauber (Eds.), *Visualization in Programming*. Lecture Notes in Computer Science Vol. 282. Berlin: Springer-Verlag. pp. 70-88.

van Sommers, P. (1984). *Drawing and cognition*. Cambridge: Cambridge University Press.

Verbrugge, Robert R. & McCarrell, Nancy S. (1977). Metaphoric comprehension: studies in reminding and resembling. *Cognitive Psychology*, **9**, 494-533.

Visser, W. (1992). Use of analogical relationships between design problem-solution representations: Exploitation at the action-execution and action-management levels of the activity. *Studia Psychologica*, **34**, 351-357.

Waisel, L., Wallace, W.A. & Willemain, T.R. (1997). Using diagrammatic representations in mathematical modeling: The sketches of expert modelers. In M. Anderson (Ed.), *Reasoning with Diagrammatic Representations II: Papers from the AAAI 1997 Fall Symposium*. Technical Report FS-97-02. Menlo Park, CA: AAAI Press, pp. 125-135.

Walker, P., Hitch, G.J., Dewhurst, S.A., Whiteley, H.E. & Brandimonte, M.A. (1997). The representation of nonstructural information in visual memory: Evidence from image combination. *Memory & Cognition*, **25**(4), 484-491.

Walsh, Paul. (1990). Imagery as a heuristic in the comprehension of metaphorical analogies. In K.J. Gilhooly, M.T.G. Keane, R.H.Logie & G.Erdos (Eds.), *Lines of Thinking: Reflections on the Psychology of Thought*. Chichester: John Wiley and Sons, pp. 237-250.

Wang, D., Lee, J. & Zeevat, H. (1995). Reasoning with diagrammatic representations. In J. Glasgow, N.H. Narayanan & B. Chandrasekaran (Eds.), *Diagrammatic Reasoning: Cognitive and Computational Perspectives*. Menlo Park, CA: AAAI Press, pp. 339-393.

Washburne, J.N. (1927). An experimental study of various graphical, tabular and textual methods of presenting quantitative material. *Journal of Educational Psychology*, **18**, 361-376 & 465-476.

Watt, S. (1997). Naive psychology and alien intelligence. In M. Garns et. al. (Eds.) *Mind versus computer*. IOS Press, pp. 46-51.

Watt, S. (1998). Syntonicity and the psychology of programming. In J. Domingue & P. Mulholland (Eds.), *Proceedings of the Tenth Annual Meeting of the Psychology of Programming Interest Group*, pp. 75-86.

Weinschenk, S., Jamar, P. & Yeo, S.C. (1997). *GUI design essentials*. New York: Wiley.

Werner, H. & Kaplan, B. (1963). *Symbol formation: An organismic-developmental approach to language and the expression of thought*. New York, John Wiley.

Whitley, K. N. (1997). Visual programming languages and the empirical evidence for and against. *Journal of Visual Languages and Computing*, **8**(1), 9-142.

Whitley, K.N. & Blackwell, A.F. (1997). Visual programming: The outlook from academia and industry. In S. Wiedenbeck & J. Scholtz (Eds.), *Proceedings of the 7th Workshop on Empirical Studies of Programmers*, pp. 180-208.

Whitley, K.N. & Blackwell, A.F. (1998). *Visual programming in the wild: A survey of LabVIEW programmers*. Technical Report CS-98-03, Computer Science Department, Vanderbilt University. Nashville, TN.

Wickens, C.D. & Carswell, C.M. (1995). The proximity compatibility principle: Its psychological foundation and relevance to display design. *Human Factors*, **37**(3), 473-494.

Willats, J. (1990). The draughtsman's contract: How an artist creates an image. In H. Barlow, C. Blakemore & M. Weston-Smith (Eds.), *Images and Understanding* . Cambridge: Cambridge University Press, pp. 235-254.

Willows, D.M. (1978). A picture is not always worth a thousand words: pictures as distractors in reading. *Journal of Educational Psychology*, **70**, 255-262.

Winner, E. & Casey, M.B.. (1992). Cognitive profiles of artists. In G.C. Cupchik & J. László (Eds.), *Emerging visions of the aesthetic process: Psychology, semiology and philosophy*. Cambridge: Cambridge University Press, pp. 154-170.

Winner, E. & Gardner, H. (1993). Metaphor and irony: Two levels of understanding. In A. Ortony (Ed.), *Metaphor and Thought* (2nd ed.). Cambridge: Cambridge University Press. pp. 425-443.

Winograd, E. & Soloway, R.M. (1986). On forgetting the location of things stored in special places. *Journal of Experimental Psychology: General*, **115**(4), 366-372.

Wood, W.T. & Wood, S.K. (1987). Icons in everyday life. In *Proceedings INTERACT '87*. Elsevier, pp. 97-104.

Wozny, Lucy A. (1989). The application of metaphor, analogy and conceptual models in computer systems. *Interacting with Computers*, **1**(3), 273-283.

Wright, P., Milroy, R. & Lickorish, A. (in press). Static and animated graphics in learning from interactive texts. In W. Schnotz (Ed.), Visual Learning with New Technologies [Special issue]. *European Journal of Psychology of Education*.

Wurman, R.S. (1997). *Information architects*. New York: Graphis Publications.

Yeung, R. (1988). MPL – A graphical programming environment for matrix processing based on constraints. In *Proceedings IEEE Workshop on Visual Languages*. IEEE Computer Society Press, pp. 137-143.

Young, R.M. (1981). The machine inside the machine: Users' models of pocket calculators. *International Journal of Man-Machine Studies*, **15**(1), 51-85.

Young, R.M. (1983). Surrogates and mappings: Two kinds of conceptual models for interactive devices. In Gentner, D. & Stevens, A. (Eds.), *Mental Models*. Hillsdale, NJ: Erlbaum, pp. 33-52.

Zacks, J., Levy, E., Tversky, B. & Schiano, D.J. (1998). Reading bar graphs: Effects of extraneous depth cues and graphical context. *Journal of Experimental Psychology: Applied*, **4**(2), 119-138.

Zacks, J. & Tversky, B. (1997). Bars and lines: A study of graphic communication. In M. Anderson (Ed.), *Reasoning with Diagrammatic Representations II: Papers from the AAAI 1997 Fall Symposium*. Technical Report FS-97-02. Menlo Park, CA: AAAI Press, pp. 144-150.

Zhang, J. (1997). The nature of external representations in problem solving. *Cognitive Science*, **21**(2), 179-217.