Visualisation and Instructional Design

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Abstract

Human cognitive architecture includes a working memory of limited capacity and duration with partially separate visual and auditory channels, and an effectively infinite long-term memory holding many schemas that can vary in their degree of automation. These cognitive structures have evolved to handle information that varies in the extent to which elements can be processed successively in working memory or, because they interact, must be processed simultaneously imposing a heavy load on working memory. Cognitive load theory uses this combination of information and cognitive structures to guide instructional design. Several designs that rely heavily on visual working memory and its characteristics are discussed in this paper.

Knowledge of human cognitive architecture is essential for instructional design, and visual cognition is a central aspect of human cognition. Not surprisingly, there are several instructional design effects that rely heavily on the manner in which humans visually process information. This paper discusses some relevant information structures, cognitive structures and instructional designs that rely on our knowledge of visual information processing.

A. Information structures

While considerable work by many researchers over several decades has been devoted to the organization of human cognitive architecture, far less effort has gone into investigating the information structures that must have driven the evolution of that architecture. Some work has been carried out by Sweller (1994) and Halford, Wilson and Phillips (1998). Sweller (1994) suggested that all information can be placed on a continuum according to the extent to which the elements that constitute the information interact. At one extreme, there is no interaction between the elements that need to be learned. They are independent. Element interactivity is low, or indeed, non-existent, and that means each element can be considered and learned serially without reference to any other element. Because elements at the low element interactivity end of the continuum do not interact with each other, there is no loss of understanding despite each element being learned individually and in isolation. Understanding is defined as the ability to process all elements that necessarily interact, simultaneously in working memory. Learning such material

imposes a low cognitive load because each element can be learned without reference to other elements. At the other extreme of the continuum, there is close interaction between the various elements that need to be learned. Element interactivity is high which means that if the material is to be understood, all of the information with its multiple elements must be processed simultaneously, imposing a heavy cognitive load.

B. Human cognitive architecture

The term "cognitive architecture" refers to the manner in which cognitive structures are organized. This section describes those aspects of human cognitive architecture relevant to visually based instructional design and around which there is broad agreement.

1. Working memory. Initially designated short-term memory (e.g. Miller, 1956) it is now more commonly referred to as working memory (e.g. Baddeley & Hitch, 1974) to reflect the change in emphasis from a holding store to the cognitive system's processing engine. Working memory can be equated with consciousness in that the characteristics of our conscious lives are the characteristics of working memory. The most commonly expressed attributes of working memory are its extremely limited capacity, discussed by Miller (1956) and its extremely limited duration, discussed by Peterson and Peterson (1959). In fact, both of these limitations apply only to novel information that needs to be processed in a novel way. Well-learned material, held in long-term memory, suffers from neither of these limitations when brought into working memory (Ericsson & Kintsch, 1995).

While initially conceptualized as a unitary concept, working memory is now more commonly assumed to consist of multiple streams, channels or processors. For example, Baddeley (e.g. Baddeley, 1992; Baddeley & Hitch, 1974) divided working memory into a visuo-spatial sketchpad for dealing with 2 dimensional diagrams or 3 dimensional information, a phonological loop for dealing with verbal information and a central executive as a coordinating processor.

A major consequence of the limitations of working memory is that when faced with new, high element interactivity material, we cannot process it adequately. We invariably fail to understand new material if it is sufficiently complex. In order to understand such material, other structures and other mechanisms must be used. Processing high element interactivity material requires the use of long-term memory and learning mechanisms.

2. Long-term memory. Because we are not conscious of the contents of long-term memory except when they are brought into working memory, the importance of this store and the extent to which it dominates our cognitive activity tends to be hidden from us. Given this hidden nature of long-term memory, it is not surprising that modern research into long-term memory post-dated research into working memory. It took some time for researchers to realize that long-term memory is not just used to recognize or recall information but rather, is an integral component of all cognitive activity including activities such as high-level problem solving. When solving a problem, it was previously assumed that knowledge stored in long-term memory was of peripheral, rather than central importance. De Groot's (1965) work on chess (first published in 1946) demonstrated the critical importance of long-term memory to higher cognitive functioning. He demonstrated that memory of board configurations taken from real games was critical to the performance of chess masters who were capable of visualising enormous numbers of board configurations. This skill depended on schemas held in long-term memory.

3. Schemas. Knowledge is stored in long-term memory in schematic form and schema theory describes a major learning mechanism. Schemas allow elements of information to be categorized

according to the manner in which they will be used. Thus, for example, we have a schema for the letter *a* that allows us to treat each of the infinite number of printed and hand-written variants of the letter in an identical fashion. Schemas first became important cognitive constructs following the work of Piaget (1928) and Bartlett (1932). They became central to modern cognitive theory, especially theories of problem solving, in the 1980's. As well as the work of de Groot (1965) and Chase and Simon (1973), Gick and Holyoak (1980; 1983) demonstrated the importance of schemas during general problem solving and Larkin, McDermott, Simon and Simon (1980) and Chi, Glaser and Rees (1982) demonstrated the critical role of schemas in expert problem solving. As a consequence of this work, most researchers now accept that problem solving expertise in complex areas demands the acquisition of tens of thousands of domain-specific schemas. These schemas allow expert problem solvers to visually recognize problem states according to the appropriate moves associated with them. Schema theory assumes that skill in any area is dependent on the acquisition of specific schemas stored in long-term memory.

Schemas, stored in long-term memory, permit the processing of high element interactivity material in working memory by permitting working memory to treat the many interacting elements as a single element. As an example, anyone reading this text has visual schemas for the complex squiggles that represent a word. Those schemas, stored in long-term memory, allow us to reproduce and manipulate the squiggles that constitute writing, in working memory, without strain. But, we are only able to do so after several years of learning.

4. Automation. Everything that is learned can, with practice, become automated. After practice, specific categories of information can be processed with decreasing conscious effort. In other words, processing can occur with decreasing working memory load. As an example, schemas that permit us to read letters and words must initially be processed consciously in working memory. With practice they can be processed with decreasing conscious effort until eventually, reading individual letters and words becomes an unconscious activity that does not require working memory capacity. Schneider and Shiffrin (1977) and Shiffrin and Schneider (1977) demonstrated the contrast between conscious and automated processing. Kotovsky, Hayes and Simon (1985) demonstrated the benefits of automated processing to problem solving skill. High element interactivity material that has been incorporated into an automated schema after extensive learning episodes can be easily manipulated in working memory to solve problems and engage in other complex activities.

C. Some Instructional Effects

Cognitive load theory (Sweller, 1988; 1994; 1999; Sweller, van Merrienboer, & Paas, 1998) deals with the interaction of information and cognitive structures and the implications of that interaction for instruction. There are many instructional effects that follow from the theory. Those effects that rely on aspects of visualisation will be discussed in this section.

1. The split-attention effect. Consider a student attempting to study a conventionally structured worked example such as that of Figure 1. The diagram in isolation provides no instruction. The associated statements such as *Angle DBE = Angle ABC* are unintelligible without a diagram. Meaning can only be derived from the worked example by mentally integrating the diagram and the statements. Mental integration requires working memory resources because learners must search for referents. When a geometry statement refers to *Angle ABC*, learners must search the diagram for *Angle ABC* in order to understand the statement. Locating referents requires working memory resources that are unavailable for learning.

A

60^0

B

D

40^0 C

E
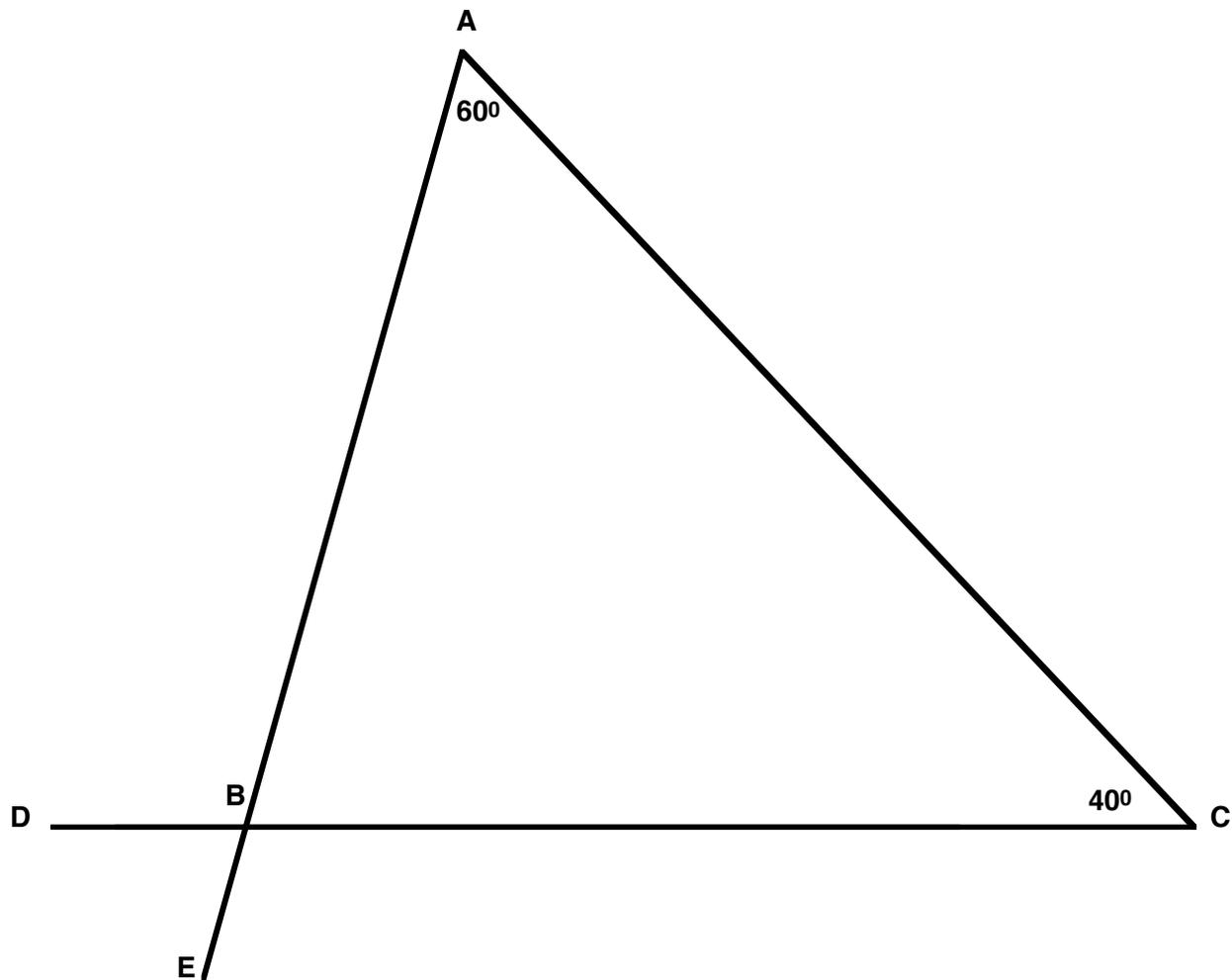
In the above figure, find a value for Angle DBE.
Solution:
Angle ABC = 180^0 – Angle BAC – Angle BCA (Internal angles of a triangle add to 180^0
  = 180^0 – 60^0 – 40^0
  = 80^0
Angle DBE = Angle ABC (Vertically opposite angles are equal)
  = 80^0

Figure 1: An example of a conventional, split-attention diagram and text

The working memory load can be reduced by physically integrating diagrams and statements. Rather than placing statements below or next to the diagram as normally occurs, relevant statements can be incorporated within the diagram so that a search for referents is eliminated (see Figure 2). If conventionally structured worked examples are compared with physically integrated examples, results normally demonstrate an advantage for the integrated versions resulting in the split-attention effect. Various versions of the effect have been demonstrated using a wide variety of instructional materials under a wide variety of conditions (Bobis, Sweller & Cooper, 1993; Cerpa, Chandler & Sweller, 1996; Chandler & Sweller, 1992; 1996; Mayer & Anderson, 1991;

1992; Mwangi & Sweller, 1998; Sweller, Chandler, Tierney and Cooper, 1990; Tarmizi & Sweller, 1988; Ward & Sweller, 1990).
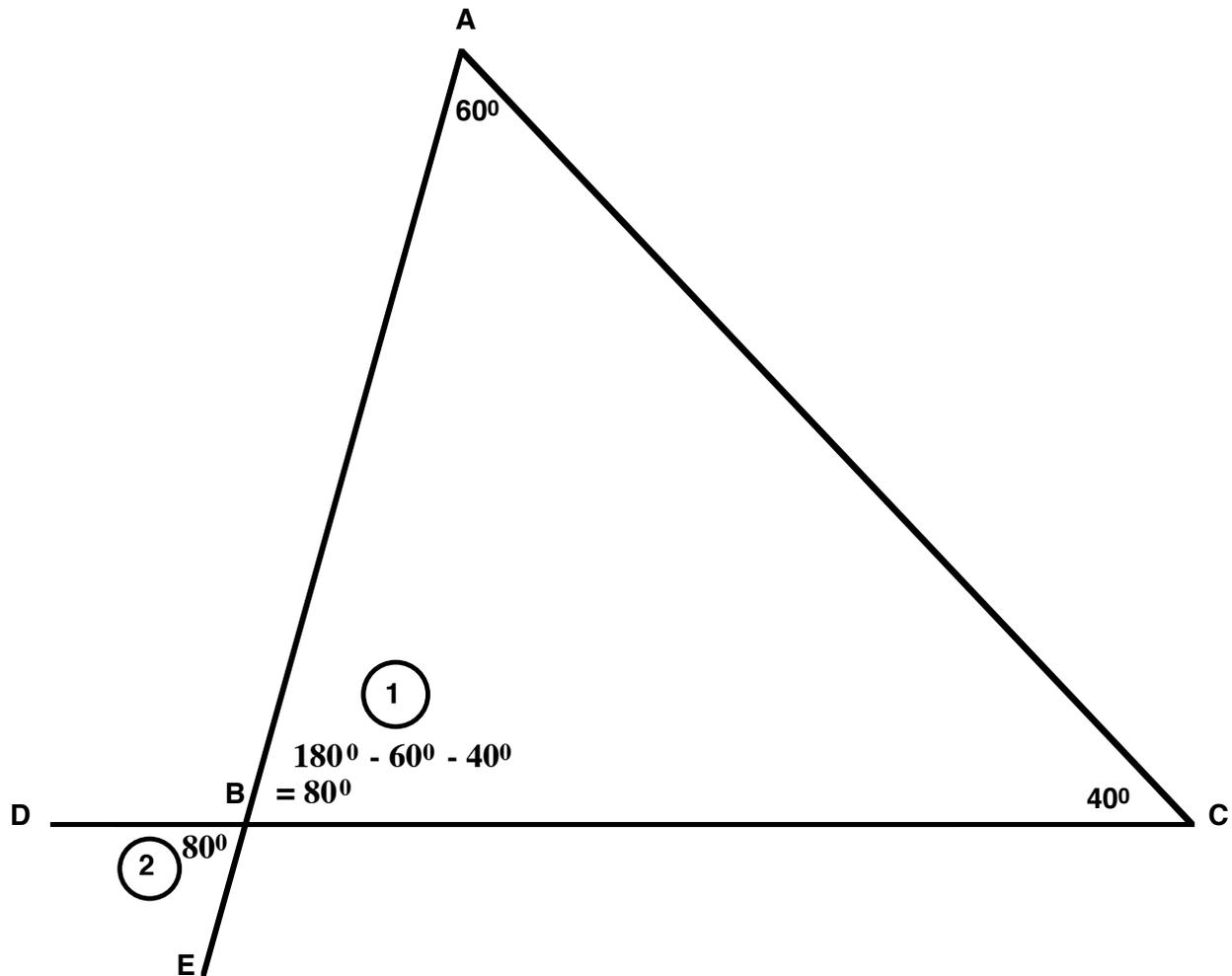
A

60^0

$180^0 - 60^0 - 40^0$

1

$= 80^0$

B

40^0

D

C

2

80^0

E

Figure 2: An example of an integrated diagram and text

2. The modality effect. While physical integration of multiple sources of information can be highly effective, there is an alternative that is equally effective and under some circumstances, may be preferable. The split-attention effect relies on the visual modality with visual search being reduced by the use of physical integration. Visual search means that the visual channel only (the visuo-spatial sketchpad of Baddeley, 1992 and Baddeley & Hitch, 1974) is being used and overloaded under split-attention conditions. There is considerable evidence that effective working memory can be increased by using dual rather than a single modality (e.g. Penney, 1989). While the visual and auditory processors of working memory are not fully separate in the sense that one does not obtain a simple additive increase in processing capacity by presenting some material visually and some in auditory mode, there is considerable empirical evidence of a measurable increase in working memory capacity when using both modalities (Allport, Antonis,

& Reynolds, 1972; Brooks, 1967; Frick, 1984; Levin & Divine-Hawkins, 1974). From a theoretical perspective, capacity should increase to the extent that visual and auditory processors can function autonomously without sharing other cognitive structures that limit capacity. Some of the empirical evidence of an increase in working memory capacity when using both modalities also provides evidence for a partial autonomy of the auditory and visual channels.

The possibility of increasing working memory capacity by using dual rather than a single modality should have instructional consequences. For example, under split-attention conditions, rather than presenting a diagram and written text that should be physically integrated, it may be possible to present a diagram and spoken text. Because the diagram uses a visual modality while speech uses the auditory modality, total available working memory capacity should be increased resulting in enhanced learning.

The instructional modality effect occurs when learners, faced with two sources of information that refer to each other and are unintelligible in isolation, learn more when presented with one source in visual mode and the other in auditory mode rather than both in visual mode. This effect has been demonstrated on a number of occasions (Jeung, Chandler & Sweller, 1997; Mayer & Moreno, 1998; Moreno & Mayer, 1999; Mousavi, Low & Sweller, 1995; Tindall-Ford, Chandler & Sweller, 1997).

3. The redundancy effect. Both the split-attention and the modality effects occur under very specific conditions. They are only obtainable when multiple sources of information refer to each other and are unintelligible in isolation. For example, a diagram and text will not yield either the split-attention or the modality effects if the diagram is fully intelligible and fully provides the information needed, with the text merely recapitulating the information contained in the diagram in a different form. Under such circumstances, the text is redundant. The redundancy effect occurs when additional information, rather than having a positive or neutral effect, interferes with learning. For example, rather than integrating a diagram with redundant text or presenting the text in auditory form, learning is enhanced by eliminating the text.

There are many different forms of redundancy. As described above, diagram/text redundancy occurs when a self-explanatory diagram has additional text re-describing the diagram (Chandler & Sweller, 1991). Mental activity/physical activity redundancy occurs when, for example, learning how to use a computer application by reading a text has the added physical activity of using the computer (Cerpa, Chandler & Sweller, 1996; Chandler & Sweller, 1996; Sweller & Chandler, 1994). Either reading the text in a manual or surprisingly, physically using a computer, can be redundant and interfere with learning. Summary/detailed exposition redundancy occurs when a summary alone results in enhanced learning compared to a summary plus a full exposition (Mayer, Bove, Bryman, Mars & Tapangco, 1996; Reder & Anderson, 1980; 1981) Lastly, auditory/visual redundancy occurs when the same material, presented simultaneously in written and spoken form, results in a learning decrement compared to the material presented in written or auditory form alone (Kalyuga, Chandler, & Sweller, 1999; 2000; Mayer, Heiser & Lonn, 2001;).

The redundancy effect is one of the more surprising cognitive load effects with many people finding it quite counterintuitive. Most of us feel that even if additional explanatory material is not beneficial, at the very least it should be neutral. In fact, the addition of redundant information can have strong, negative consequences. The effect can be understood in cognitive load theory terms. If one form of instruction is intelligible and adequate, providing the same information in a different form will impose an extraneous cognitive load. Working memory resources will need to be used to process the additional material and possibly relate it to the initial information. It is

likely to be only after the learner has processed the additional information that he or she will be aware that the activity was unnecessary. At that point, the damage may have been done.

4. The element interactivity effect. The split-attention, modality and redundancy effects all occur as a consequence of instructional procedures designed to reduce working memory load. It might be expected that the instructional procedures would only be effective where the material being learned imposed an intrinsically high cognitive load. If material does not impose a high cognitive load, the additional load due to inadequate instructional procedures may not matter a great deal because working memory capacity may not be exceeded. An extraneous cognitive load due to inadequate instructional procedures may be irrelevant if the intrinsic cognitive load imposed by the structure of the information is low. Since low element interactivity material has a low intrinsic cognitive load, we can predict that cognitive load effects may disappear when learning such material. The effects may only be obtainable using high element interactivity material. Chandler and Sweller (1996) and Sweller and Chandler (1994) demonstrated that the split-attention and redundancy effects could readily be demonstrated using high element interactivity material but disappeared when low element interactivity material was used. Tindall-Ford, Chandler and Sweller (1997) similarly found that the modality effect could only be obtained using high element interactivity material. Marcus, Cooper and Sweller (1996) found that diagrams for which we have schemas facilitated understanding when compared to text but only under conditions of high element interactivity.

The finding that cognitive load effects can only be obtained using high element interactivity material demonstrates the element interactivity effect. It consists of an interaction between the split-attention, redundancy and modality effects and the complexity (as measured by element interactivity) of the material being learned. While it has not been tested using other cognitive load effects, there is every reason to suppose it could be obtained with all other effects based on a limited working memory.

5. The imagination effect. Assume a novice who has acquired some limited schemas. To attain relatively high levels of expertise, further learning will need to include automation of the previously acquired schemas that normally includes continuing to study the material until desired levels of performance have been attained. An alternative is to attempt to imagine the procedures that have been learned. Imagining requires the learner to mentally "run through" or visualise the procedures in working memory. For high element interactivity material, processing information in working memory is impossible until schemas have been acquired. Once they have been acquired and the learner has moved towards the right of the matrix of continua, imagination techniques should be feasible and practice through imagination should assist in automation. Continuing to study the material should be unnecessary because studying high element interactivity material is designed to provide the guidance necessary to reduce search while acquiring schemas. If schemas have already been acquired, there is no longer any need to provide instructional guidance to reduce search because. Using those schemas to imagine the procedures learned should facilitate further learning through automation in a manner that studying the instructions may not.

Cooper, Tindall-Ford, Chandler and Sweller (2001) tested this hypothesis and found that learners given instructions to "imagine" a set of procedures that needed to be learned performed better than learners given conventional "study" instructions. This imagination effect was only obtained using learners with sufficient knowledge to be able to process all of the required information in working memory. For complete novices who were unable to process the high element interactivity material in working memory, a reverse imagination or "study" effect was

obtained with "study" instructions proving superior to "imagination" instructions. In other words, the effect obtained depended on the levels of expertise of the learners. Higher levels of expertise could reverse the effect obtained. The ideal form of instruction depended on the expertise of the learners.

The instructional designs described in this section differ from many instructional designs in that they are very closely tied to our knowledge of information structures and human cognitive architecture. Indeed, they were generated directly from that knowledge. The designs not only flow from our knowledge of visual working memory, they can provide additional information concerning its characteristics.

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