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WORKING MEMORY: A MENTAL SPACE FOR DESIGN AND DISCOVERY

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1. Introduction

The design process can be viewed as the product of human creative thinking; the skills of generating new knowledge from old within the external constraints of the items to be designed. Expert designers have high level skills that assist them in this process. However design effectiveness and the training of design skills could benefit from an understanding of how human cognition undertakes the process of creative thinking without such specialist training, and what aspects of human cognition impede or enhance this process. In this paper, I shall discuss some of the empirical research and theoretical developments that have contributed to an understanding of on-line visual and spatial cognition that might support creative thinking. The paper starts with a discussion of a particular theoretical framework referred to as working memory, and some of the empirical work that has used this framework to explore visual and spatial cognitive functions. This discussion will set the background of the general thesis for the chapter that visual and spatial aspects of working memory might play important roles in creative thinking and design. This will lead to a discussion of the ways in which human working memory and the use of external aids to thinking might facilitate or constrain aspects of the creative process. The paper will end with a discussion of why human beings might have developed a working memory system, with the possibility that its primary purpose is to support the process of generating new knowledge.

2. Working Memory

Working memory refers to the means by which human beings maintain, on a temporary basis, information that is required for successful performance of a range of everyday tasks from mental arithmetic through reasoning and problem solving, to planning a route. It also appears to play important roles in acquiring new knowledge and in some aspects of retrieving previously acquired knowledge. It deals with the manipulation as well as the temporary storage of information, and handles visual and spatial information as well as words, letters and numbers. As such, working memory enjoys a much broader role in cognition than does the more traditional concept of short-term memory. The latter has focused on immediate recall of sequences of verbal items, based on tasks akin to remembering telephone numbers long enough to press the telephone keys in the correct order. Working memory is more complex, but has proved to be extremely useful in helping cognitive psychologists understand important aspects of everyday cognition.

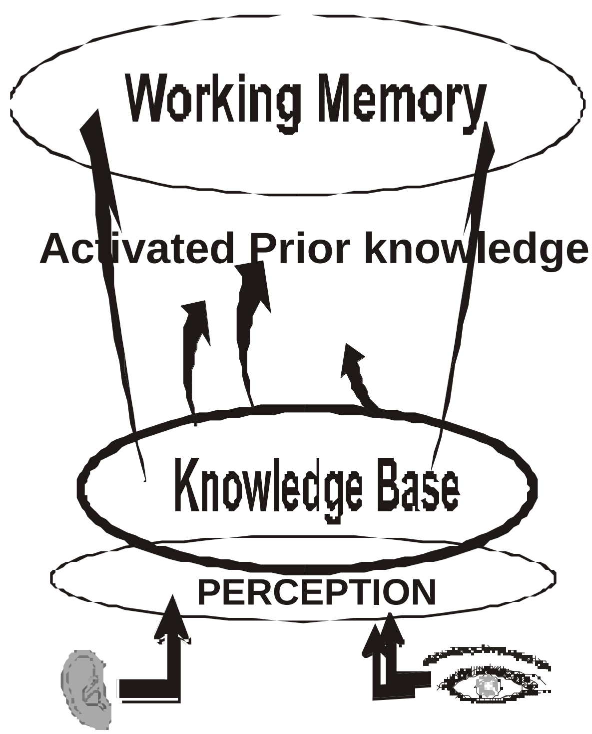

Figure1. Working memory as a single, general purpose workspace

Because of its utility coupled with its apparent complexity, there are several different theoretical frameworks for working memory, and a comprehensive discussion of these alternative views is presented in Miyake and Shah (1999). Figure 1 illustrates one possible view of working memory as a single, general purpose mental resource that can be used as a temporary memory store, for directing attention, as the recipient of activated prior knowledge, and for manipulation of the information it holds. One implication of this framework, is that as more of the working memory resource is required for memory storage, then less is available for directing attention or for manipulating information and vice versa. In so far as we can assume that working memory supports key aspects of creative thinking, this kind of framework would suggest that if the current temporary memory load is high, then there would be a very limited capacity for creative manipulation of that information.

However there is a significant body of evidence to suggest that the framework indicated in Figure 1 is too simplistic and is misleading. This conclusion arises from a wide range of experimental studies with healthy adults and children, from reports of very specific cognitive deficits following brain damage, and patterns of brain activation detected by brain imaging techniques such as PET or fMRI. It appears that human working memory is better viewed as comprising a range of specialised mental systems each of which deals with memory for particular kinds of information or with information manipulation (including rehearsal) (e.g. Baddeley and Hitch, 1974; Baddeley and Logie, 1999). One view of this ‘multiple component’ working memory is illustrated in Figure 2. One pair of components, the visual cache and the inner scribe, are thought to support respectively temporary memory for the visual appearance and layout of a scene together with pathways or movements through the scene. A second pair of components, the phonological store and ‘inner speech’ offer respectively temporary memory for the acoustic and phonological properties of words, letters and numbers together with serial ordered, subvocal (mental) rehearsal of those items. The component labelled ‘executive functions’ comprises a range of such functions, that include the co-ordination of the memory and rehearsal systems, and for manipulation of information that is held in the temporary memory systems or is generated from the knowledge base of skills and information acquired from past experience (for reviews see Baddeley and Logie, 1999; Logie and Della Sala, in press).

Although presented as a set of identifiably separate components, it is clear that in the healthy brain and for most everyday cognitive tasks, the systems within working memory act in concert. For example, if we are trying to imagine what our living room would look like with the furniture rearranged, then we would hold in mind the names of the items of furniture, their shape and location, but would also have some idea from our past experience of how heavy these items are, how easily they could be moved, and some information about the costs of buying new furniture or the potential health care consequences of unsuccessful attempts to shift the piano! Therefore, what appears to be primarily a visuo-spatial manipulation task, involves verbal information and a great deal of prior knowledge, as well as the processes of mentally imagining the potential appearance of the room following its reconfiguration. In general terms, I would argue, this is also the basis for the use of working memory in support of design and creative thinking.

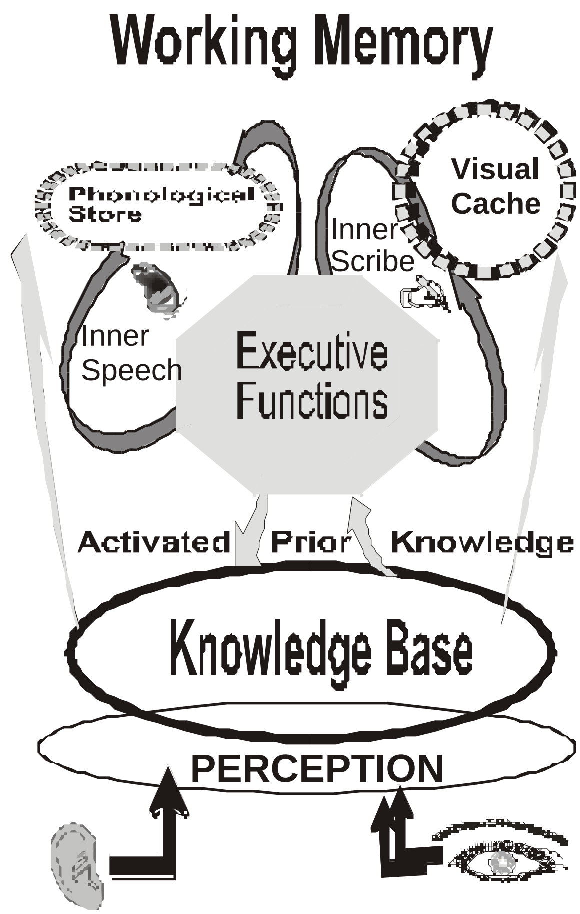

Figure 2. Working memory as a multiple component workspace

This observation that working memory incorporates some of our existing knowledge, raises an additional important feature of both Figures 1 and 2, namely that there is no direct link between working memory, and the processes involved in perception of the current environment. In particular, the contents of working memory incorporate some form of interpretation based on prior knowledge. Working memory does not handle raw sensory patterns of edges, contours, shades and textures directly from the environment. Rather, it deals with objects and shapes that have been identified by the processes of perception and that draw on our knowledge base of past experience. Therefore, in looking at my desk, the contents of working memory comprise a desk lamp, a computer screen, a coffee mug, a telephone and a range of books and paper. The identification of these objects is possible only if the patterns of light and shade, edges, textures and contours in the visual field have been successfully perceived as specific objects, and successful identification relies on my previous experience of these objects and objects of this kind. This process of identification could not be so readily accomplished by a new born baby. Identification of the objects also would present something of a challenge to people who had never experienced computer technology or electrical light sources. In sum, perception involves the activation of previously stored knowledge in response to a particular configuration of stimuli from the environment. Much of perception, including object identification, is automatic and requires no direct involvement of working memory. As healthy adults, what we deal with in working memory is the product of what has been activated from our knowledge base.

This rather distant, and indirect link between perception and working memory is somewhat controversial, since a great deal of research in cognitive psychology is predicated on the assumption that there is a fairly intimate relationship between perception and mental representations, such as mental images. However the case is strong for the contents of mental images to be interpreted (e.g. Beschin, Cocchini, Della Sala and Logie, R.H., 1997; Logie, 1995), and this has some important implications for the ways in which working memory can support creative thinking.

3. Cognitive Limitations on Creativity

Creative thinking was described above as a means to generate new knowledge from old. When human beings generate a new idea or a physical artefact that is deemed to be creative, one means to do so is to recombine or reinterpret some aspects of their existing knowledge. The fact that the contents of working memory are interpreted at some level could act to inhibit their ability to generate new interpretations. This is one possible reason why creative thinking is difficult for many people, and why few individuals can excel in this endeavour.

One striking example of a failure to dispense with an initial interpretation of a stimulus was described by Chambers and Reisberg (1985; 1992) who explored the use of a range of ambiguous figures. In their initial experiments, volunteers were shown a drawing of an ambiguous figure, for example, the ‘duck-rabbit’ shown in Figure 3. Each volunteer was allowed to view the drawing for just 2 seconds, after which they were to report from memory, what the drawing depicted. Roughly half of the volunteers reported that they had seen a drawing of the head of a rabbit. The other half reported seeing the head of a duck. When asked if they could see the figure as depicting anything else, none of the volunteers were able to report the alternative interpretation. However, when asked to draw the figure from memory, they could then report the alternative interpretation from looking at their drawing, even although they could not do so from their imagery. Chambers and Reisberg carried out a number of follow up studies all of which led to the same conclusion, that volunteers had great difficulty in changing their initial interpretation that was associated with immediate memory for a recently viewed drawing. So, not only was there an interpretation linked to their representation in working memory, but removing or altering that interpretation was extremely difficult when based on the representation in working memory alone.

Subsequent studies by other researchers have shown that some volunteers can report alternative interpretations of ambiguous figures, if some measures are taken to try to prevent the initial interpretation being formed. For example, Brandimonte and Gerbino (1993) asked volunteers to suppress articulation by means of repeating aloud an irrelevant word during the brief time that they were viewing the ambiguous figure. This resulted in somewhere between 15% and 30% of individuals able to report the alternative interpretations of the figures from their images. Moreover, Brandimonte, Hitch and Bishop (1992a; 1992b) showed that figures that are easy to name are more difficult to reinterpret in mental imagery than are items that are difficult to name. Brandimonte et al. also demonstrated that overt suppression of articulation removed some of the effects of ‘nameability’. In other words, when a stimulus can be readily identified from initial perception, this interpretation forms part of the representation in working memory. Articulatory suppression can act to inhibit some aspects of this initial interpretation, thereby increasing the possibility that novel or alternative interpretations can be generated. (for a detailed discussion see Cornoldi, Logie, Brandimonte, Kaufmann and Reisberg, 1996).

Although the above studies demonstrate that the interpretation in working memory can be made more flexible, it is striking that only a minority of participants show the benefit of these manipulations in their performance. Therefore, these findings do not undermine the general thesis that 'first impressions' have a major effect on the contents of working memory, and can act to inhibit our ability to think about our recent experiences in new and different ways.

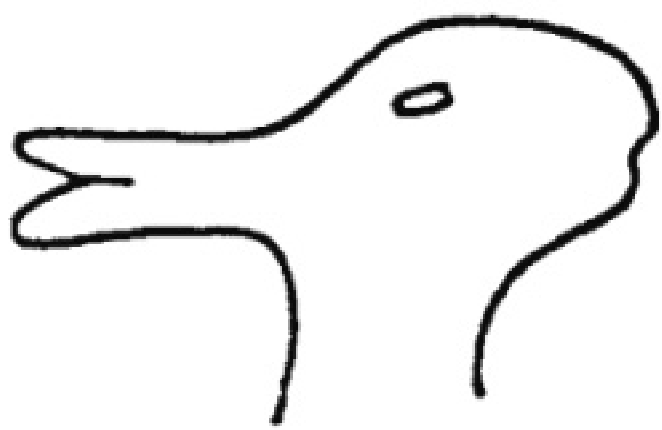

Figure 3. The duck/rabbit ambiguous figure

The findings from studies with ambiguous figures echo those from studies of mental synthesis tasks (see also chapter by Pearson, this volume). In these tasks, volunteers are given the names of a small number of familiar, canonical shapes, such as a circle, a triangle and a square. They are asked to generate a mental image of these items and to combine the shapes mentally such that they form a recognisable object. An example of a production from experiments reported by Barquero and Logie (1999) is shown in Figure 4. One crucial feature of these experiments is that volunteers are asked to generate a name for the mental image that they form before they draw their image. After drawing the image, they are then asked if they wish to change the name that they generated. The drawings, together with their names are then shown to independent judges who are asked to rate the degree of correspondence between each name and the drawing given. The judges rated the second name (produced after drawing) as having a greater degree of correspondence with the drawing than did the first name given. In other words, the volunteers were better able to interpret their newly generated object forms if they could inspect their own drawing of the mental image than if they relied on the mental image alone.

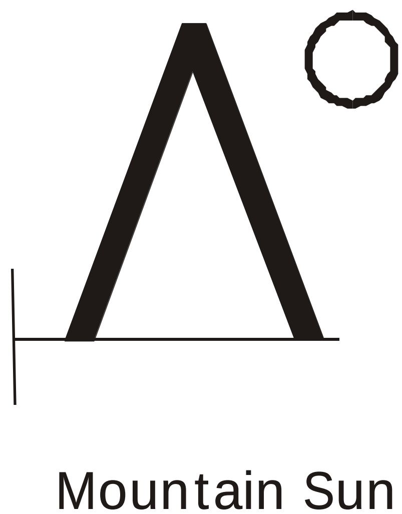

Figure 4. Example participant drawing from mental synthesis of a triangle, a circle and the letter ‘T’ (Barquero and Logie, 1999)

In a further experiment, Barquero and Logie asked volunteers to combine mentally, shapes of real objects, such as a cigar, a glass and a banana. Again, they were given the names of the shapes and were asked to combine these shapes to form a recognisable object that was different from the component parts. A successful attempt from one volunteer is shown in Figure 5. However, many volunteers had difficulty performing this task, and when productions were judged independently, the ratings given were significantly poorer than those that had been allocated to the drawings and names derived from the canonical shapes. It appeared that volunteers had difficulty divesting the object identity from its shape to allow mental manipulation and combination of the shapes to form different objects. That is, the component objects to be combined had a form of ‘semantic baggage’ that was difficult to shake off.

The results above might be interpreted as suggesting that mental manipulation is simply a demanding cognitive task, and the problems arose from simply holding the shapes in memory while they were combined. Perhaps real object shapes are more complex visually than are canonical shapes such as circles, squares and triangles, and are therefore more difficult to hold in mind. However, if this were the case, we would have expected volunteers to miss out some of the objects altogether, and there was no evidence that this was any more likely with the real object shapes than with the canonical shapes. Increasing the number of shapes to be held and combined resulted in participants forgetting to include some of the shapes. However the number of shapes had no impact on the judged correspondence between drawing and name; ratings were no different for successful combinations of five shapes than they were for combinations of three shapes (see also Pearson, Logie and Gilhooly, 1999). That is, number of shapes places a load on the storage capacity of working memory, but it does not appear to enhance or to inhibit the process of mental discovery. What does affect mental synthesis performance is the extent to which the images have associated meaning. These additional observations reinforce the view that it was the semantic interpretation of the items that was crucial for inhibiting mental synthesis, not their complexity or number.

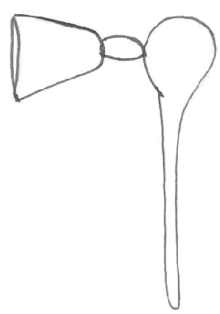

Figure 5. Example participant drawing from mental synthesis of the shapes of a dustbin, a rugby ball and a tennis racquet (Barquero and Logie, 1999)

4. Working Memory and Other Design Tools

The design tools available to human designers may comprise mental strategies or acquired skills, prior knowledge of design principles or memory for examples of previous, similar design problems and their solutions or the capacities, as well as the characteristics, and limitations of working memory. Design tools also may be external aids to design such as sketching, or computer aided design packages. In this paper, I have focused on the role of human working memory in the process of creative thinking available to all healthy adults, rather than the specialist cognitive design tools available to the expert. The effectiveness of external design aids as well as of working memory is likely to vary with the expertise of the designer (see paper by Pearson, this volume). However, the utility of each of these external design tools generally has been assumed rather than formally assessed, and this raises the question as to whether mental discovery is enhanced or inhibited by their use.

For example, Anderson and Helstrup (1993) showed that imaging along with paper and pencil support (sketching) can result in either no benefit or even in less creative thinking that using imagery alone, at least for variations of the mental synthesis task. One possible reason for this is that paper and pencil drawings and diagrams cannot convey *dynamic* manipulations, and therefore they may not provide a suitable medium for creative synthesis. In contrast, computer-based graphical packages allow for dynamic manipulations to be carried out which may be similar to those that occur during visual imagery. Where paper and pencil seemed to help was as a memory aid, allowing the volunteers to remember which items they had to combine mentally.

In a recent series of experiments, David Pearson and I have explored further, the potential impact of a range of possible external aids in mental synthesis tasks. These experiments followed the general procedure used by Pearson et al. (1999) and Barquero and Logie (1999). Volunteer participants with no specific design training were shown a set of 15 two-dimensional generic and familiar shapes, each of which was associated with a verbal label (i.e., circle, capital 'D', number 8, triangle etc.). They were asked to learn the precise appearance of the shapes so that they could be accurately imaged and drawn in response to each verbal label.

During the experimental phase of the standard 'imagery alone' version of the task participants were presented with a set of the verbal labels for three to six shapes drawn randomly from the total pool of fifteen. Participants were required to form a mental image of a recognisable object or pattern that included all of the shapes named for that trial. In so doing, the imaged shapes could be manipulated into any size or orientation, but could not be distorted; for example, a circle had to retain a circle shape and could not be used as an oval. Participants were given a period of two minutes in which to generate a completed pattern. After this period participants were first asked to give a short verbal description of the resulting imaged pattern, and then to draw their imaged pattern on to a sheet of paper. This procedure was adopted to ensure that the verbal naming of the imaged pattern was not influenced by the stimulus support benefits of being allowed to draw the synthesised image as discussed earlier (Pearson et al., 1996; Barquero and Logie, 1999). If participants were unable to generate a synthesised pattern within the allotted two minutes, they were instructed to write 'no pattern' for the verbal label, and then to draw as many of the presented shapes as they could remember. This procedure allowed for a measure of memory that was independent of whether or not the participants could generate a recognisable pattern on every trial.

All participants performed the synthesis task using imagery alone, and then in one of three secondary task conditions. In one condition, participants were asked to carry out the synthesis task while attempting to draw in the air with their preferred hand as a form of stimulus support. In a second condition, participants were given a pencil and a pad of blank paper, and were asked to sketch their various attempted combinations while carrying out the synthesis task. Finally, in a third condition, participants performed the synthesis task using CorelDraw!™, a commercially available computer based graphics package that allows two-dimensional displays to be transformed and manipulated dynamically on screen.

Results showed that neither drawing in the air nor paper and pencil support resulted in any benefit compared with imagery alone. There was a modest increase in the number of legitimate patterns obtained with the graphics package, although the difference was marginal ($p=0.052$). However, participants were much less likely to forget to include all of the shapes on each trial if they were allowed to use paper and pencil or computer graphics support. In a follow up experiment we examined the same set of tasks and forms of stimulus support but with shapes that were more complex visually. Again, the graphics package and paper and pencil resulted in fewer shapes being forgotten, but showed only a modest improvement in whether the participants could generate legitimate combinations of the shapes. These findings all support the idea that external aids might provide an aid to memory, but do not necessarily aid the design process, at least with healthy, well educated individuals who have no particular training in the principles and techniques of design.

5. Creative Thinking: A Raison d'être for Working Memory

Thus far, I have argued that working memory appears to play a role in creative thinking, although the discussion has focused on how the interpreted contents of working memory might inhibit the reinterpretation necessary for creative design. Another part of the discussion has argued that external aids might only relieve the memory load involved in mental manipulation of elements of a design, but not necessarily enhance the creative aspects of design. Of course, if working memory is burdened less with storing details, then one argument could be that the use of external memory aids might free working memory resources to focus on the process of mental manipulation, reinterpretation, and creative thinking.

If working memory deals with interpreted representations, then some of the findings described above suggest that reinterpretation might require active inhibition of the current interpretation. It is also likely to require activating other knowledge from prior experience that is not immediately available from perception of the object. If we see the drawing in figure 3, then our initial perception might interpret this as the head of a rabbit. To reinterpret the figure as anything else, we have to have some way of activating other knowledge from our previous experience of objects and creatures that we have encountered. We could do this by looking again at the external drawing, turning around the paper, moving it closer or further away. Mentally, we might generate hypotheses as to what else it might be – an object shown from an unusual view perhaps, or the head of a different animal, and we might focus our visual perceptual system on the left or the right of the figure. We also have to try and inhibit the initial interpretation of the figure as a rabbit. Eventually through a combination of changing the external experience, generating hypotheses, and a mental search process we can reconfigure and reinterpret the item. In some cases, this process of hypothesis generation, manipulation, and mental search might occur successfully without an external stimulus, and indeed, the external stimulus may interfere with the mental processes. In other cases, as for the duck-rabbit example, the external stimulus may be essential.

Throughout this process, I would argue that working memory provides the mental workspace for the hypothesis generation, inhibition, mental manipulation, and mental search. At a theoretical level, working memory therefore cannot an input filter between perception and long term memory, as it is often portrayed in introductory textbooks on memory. It must deal with the product of activated representations in long-term memory (Logie, 1995, 1996). Where the activated information is incomplete or has to be reinterpreted, working memory acts as the workspace to manipulate the information and seek some means to resolve ambiguities or generate new knowledge. This points to one possible reason why we have evolved with a working memory. If we can make sense of a sensation, scenario, or experience from our current knowledge, this can happen effortlessly by activating the relevant knowledge that allows us to act appropriately for the current context. However if we are confronted by ambiguity, by implication this means that the knowledge activated by perception from the long-term store is insufficient. What knowledge is activated can be manipulated and transformed within working memory to help resolve the ambiguity. That is, working memory can generate new knowledge from old and as such would have significant evolutionary value.

This same argument can be applied to how we might start to acquire knowledge from birth. The neonate is confronted by what William James (1902, p7) referred to as 'pure sensations', in that there is no knowledge base which can offer an interpretation of perceptual input beyond pain, pleasure, and satiation of hunger or thirst. Empirical developmental studies since that time have demonstrated that babies may have rather more knowledge than James assumed. However it might be interesting to explore the concept that working memory in the neonate can generate new knowledge based on whatever information is activated in response to their current environment, thereby 'bootstrapping' knowledge. This role for working memory in generating new knowledge feeds into an evolutionary based argument for its contribution to encoding, retaining and manipulating information as well as executing actions to manipulate objects or view them from a different perspective. Both physical and mental manipulation may generate novel associations or interpretations. Physical manipulation provides external stimulus support and avoids overloading working memory capacity. It also gives us visual, tactile, motoric, kinaesthetic and other information about the object that we could not gain from mental manipulation, and this information may feed into new learning. Mental manipulation allows us to combine the percepts from real objects with novel variations on prior knowledge that those percepts activate.

In this scenario, we can all use working memory to generate new knowledge, and the fact that we have a working memory has allowed us to acquire and use the knowledge that we already have available. The properties of working memory, therefore, offer a vehicle and a set of experimental methodologies to help understand, and to help develop the human capacity for creative discovery and creative design.

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