J. S. Gero, B. Tversky and T. Purcell (eds), 2001, *Visual and Spatial Reasoning in Design, II*
Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp.

WORKING MEMORY AND EXPERTISE DIFFERENCES IN DESIGN.

What is the cognitive impact of sketching during design?

DAVID G. PEARSON AND CLARE ALEXANDER
University of Aberdeen
UK

AND

ROBIN WEBSTER
The Robert Gordon University
UK

Abstract. The Creative Synthesis task devised by Finke and Slayton (1988) has been widely used as an experimental measure of mental synthesis, but previous studies have often failed to demonstrate any significant benefits of external support on participants' performance. This paper discusses a study that examined novice and expert drawers' performance of synthesis using a modified stimuli set that was designed to increase the load on visuo-spatial working memory. The results showed a significant increase in Transformational Complexity (Anderson & Hesltrup, 1993) of patterns produced by the expert group while using sketching. It is argued that experts are more effective at using sketching interactively to increase complexity, while novices rely more on using it as a simple memory aid.

1. Introduction

On an intuitive level it appears obvious that unstructured drawing or sketching is beneficial to the design process. There are numerous reports in the literature that demonstrate the pervasive use of sketching during design (e.g., Herbert, 1988; Gross et al., 1988; Goldschmidt,1991), and the teaching of design practice is heavily dependent on encouraging the use of sketching as a means to further creativity and innovation among students.

Despite this, however, it has proved surprisingly difficult to quantify the cognitive impact made by sketching within a coherent empirical framework. The main reason for this is that the majority of existing models of human working memory have failed to explicitly address the issues of how external representations interact with internal mental representations during cognition. In a recent review of the major models of working memory Miyake and Shah (1999) have pointed out that the traditional view of external memory functioning as a simple memory aid is too simplistic, and that it fails to provide an explanation for how working memory systems can act as an interface between external and internal representations. Understanding how this interface operates will be an essential step in establishing a cognitive framework in which to interpret the beneficial effects of sketching during design.

One area of research undeniably important to this question is that concerned with peoples' ability to make novel discoveries from visual mental images. Reisberg (1996; Reisberg & Logie, 1993; Reisberg & Heuer, in press) has argued that images and percepts, unlike pictures, cannot be inherently ambiguous. While perceptual processes can reinterpret an external representation relatively easily, an internally generated mental image is interpreted within a specific frame of reference. While discoveries that are compatible with this existing reference frame can be made fairly easily, discoveries that are incompatible can be extremely difficult to make. However, this limitation can be overcome by converting the image into an external representation via sketching. Reisberg has argued that sketching can support the restructuring of a mental image by allowing the frame of reference in which it is interpreted to be changed. A dramatic demonstration of this was made by Chambers and Reisberg (1985) using the Jastrow duck-rabbit ambiguous figure. All of their participants were unable to reinterpret the figure using mental imagery alone, while a hundred percent did so when allowed to draw the figure on a piece of paper. Similar beneficial effects of drawing have been demonstrated for participants' ability to interpret figures resulting from guided image transformations (Pearson, Logie & Green, 1996; Barquero & Logie, 1999), and for the ability to detect embedded figures within patterns (Verstijnen, van Leeuwen, Goldschimdt, Haeml, & Hennessey, 1998a).

Although these studies show a clear cognitive benefit of sketching, the design process itself rarely consists of just reinterpreting a pre-existing figure. Design has been characterised as a *synthetic* process in which separate elements or components are combined together in a novel and innovative manner (Purcell & Gero, 1998). Bearing this in mind, it is therefore surprising that many experimental studies of mental synthesis have struggled to find any beneficial effect of using external representations. Many studies have made use of a procedure devised by Finke and Slayton (1988) in which participants mentally combine randomly selected alphanumeric and geometric symbols into a recognisable object or picture. Neblett et al. (reported in Finke, 1990) found no beneficial effect of allowing participants to manipulate the symbols using printed acetates in contrast with a group who relied on visual imagery alone. In a similar vein, Anderson and Helstrup (1993) examined performance of creative synthesis between participants who were allowed to sketch during the synthesis task and participants who relied on imagery alone. They measured performance using a variety of variables including a Transformational Complexity (TC) measure which scored the extent to which the presented symbols had been rotated, mirror-imaged, changed in size or embedded together. They found no significant differences in transformational complexity between the sketch and imagery-alone conditions.

One explanation for this null result has been offered by Verstijnen, van Leeuwen, Goldschimdt, Haeml, and Hennessey (1998b). In a similar manner to Reisberg (1996) they have argued that combining symbols together is relatively easy to accomplish using imagery alone, but that successful restructuring of an image requires the external support of a sketch. They conducted an experiment in which expert sketchers (design students) completed the Finke and Slayton task either with or without the support of sketching. Overall there were was no difference in the transformational complexity measure between the two groups. However, when the four components of the TC measure were analysed separately there appeared to be an increase in the frequency of size difference transformations, although this effect was only marginally significant. In contrast, there was a trend for transformations that did not alter the structure of the symbols (mirror-imaging and rotation) to show a slight decrease in occurrence within the sketching condition. Verstijnen et al. suggested that the null effect reported by Anderson and Helstrup could be the result of opposing trends canceling each other out as restructuring and non-restructuring components were combined in the TC measure.

However, there is a danger that both the Verstijnen et al. and Anderson and Helstrup findings may result from specific characteristics of the Finke and Slayton procedure rather than general cognitive processes associated with mental synthesis. One problem is that the original stimuli set used by Finke and Slayton (Figure 1) may actively discourage certain types of manipulations from being carried out. The majority of the symbols are symmetrical, which means there is no value in carrying out mirror-imaging transformations. With a symbol such as a circle the only valid transformations that can be carried out are size changes or embedding. The opposing trend reported by Verstijnen et al. could therefore result from a ceiling effect in which there was no further scope for an increase in non-restructuring transformations in the sketching condition.

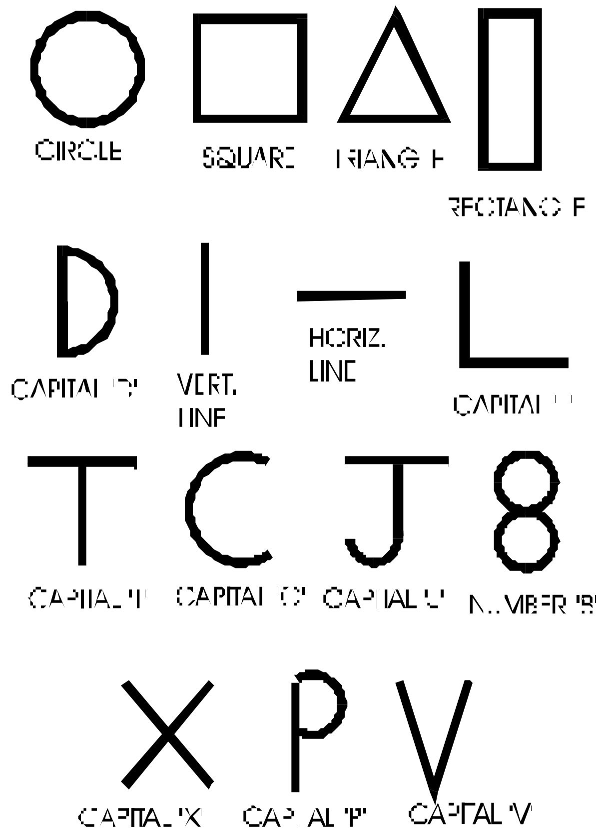

Figure 1. Finke and Slayton's (1988) original stimuli set of 15 items.

Another potential drawback of using the original stimuli set is that they encourage participants to store material using verbal rather than visual working memory. Pearson et al. carried out a series of studies in which they examined how verbal, visual and spatial distracters affected participants performance of mental synthesis (Pearson, Logie & Gilhooly, 1999). The results revealed that participants relied heavily on using the phonological loop component of working memory to maintain symbol identity. Figure 2 represents how various components of the working memory system are involved during the Finke and Slayton procedure. It is based on a model in which visual working memory is divided into a visual buffer in which conscious visual images are represented and a separate visual short-term cache (see Pearson, in press; Logie, 1995).

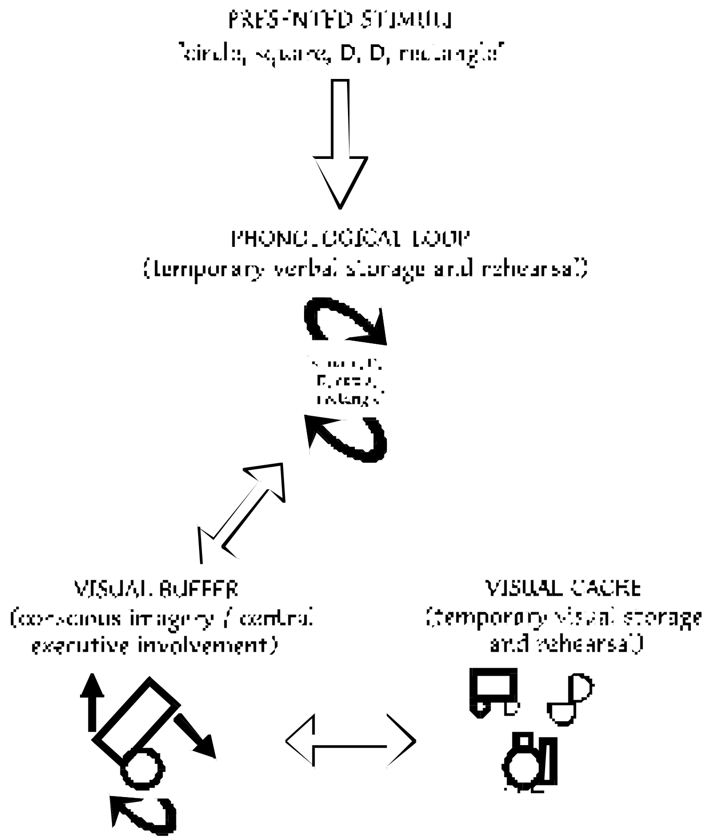

Figure 2. Involvement of verbal and visual working memory systems during creative synthesis (taken from Pearson et al., 1999).

In the standard Finke and Slayton procedure the shapes are verbally presented to participants via their verbal labels. This material will therefore gain direct access to the phonological store component of working memory and be maintained there via the operation of the articulatory loop (Baddeley, 1986; Baddeley & Lewis, 1981). Participants then use these verbal representations to generate visual images of the symbols in their visual buffer. However, the verbal representations continue to be maintained within the loop so as to provide a memory back-up for the symbols that is separate from the use of visual imagery. Such a strategy represents an effective means of spreading the cognitive load of the task across the whole of the working memory system. Maintaining the presented symbols as verbal representations considerably reduces the load on the visuo-spatial and central executive components, as there is less requirement to maintain the symbols to be combined purely in a visual form (Pearson & Logie, 2000). This strategy is encouraged because there is a direct correspondence between the verbal labels presented to participants and their visual form as stored in long-term memory. It is therefore predicted that if the correspondence between labels and symbols was weakened then the strategy of maintaining information in the phonological loop would no longer be optimal, and participants would be forced to increase storage within the visual buffer and visual cache components.

This paper reports a study taken from Pearson, Alexander, Rockenbach and Webster (in prep.) which attempts to test this prediction using a modified version of the original Finke and Slayton stimuli set. Groups of expert and novice drawers were asked to complete the creative synthesis task either using mental imagery alone or with the addition of sketching. The hypothesis was that the modified stimuli set would reveal clearer benefits of sketching during synthesis than has been found in previous studies.

2. Method

Twenty-six male and six female undergraduate students volunteered to take part in the study. Sixteen participants were architecture students in their fifth year of study at the Scott Sutherland School of Architecture, and were classified as expert sketchers. The novice sketchers consisted of arts and social science students in their fourth year of study at the University of Aberdeen. The mean ages were 23.5 for the experts and 22.9 for the novices. Although it is acknowledged that participants classified as expert sketchers were still in the process of learning about the design process, they had nonetheless had at least four years of training in using sketching in comparison to the novice sketcher group.

All participants completed 10 mental synthesis trials using imagery alone, and 10 trials with the addition of sketching. The order in which the imagery-alone and sketching conditions was completed was counter-balanced across participants. On each trial the experimenter read out the verbal labels for five randomly selected symbols which were drawn from a total set of 15 items (Figure 3).

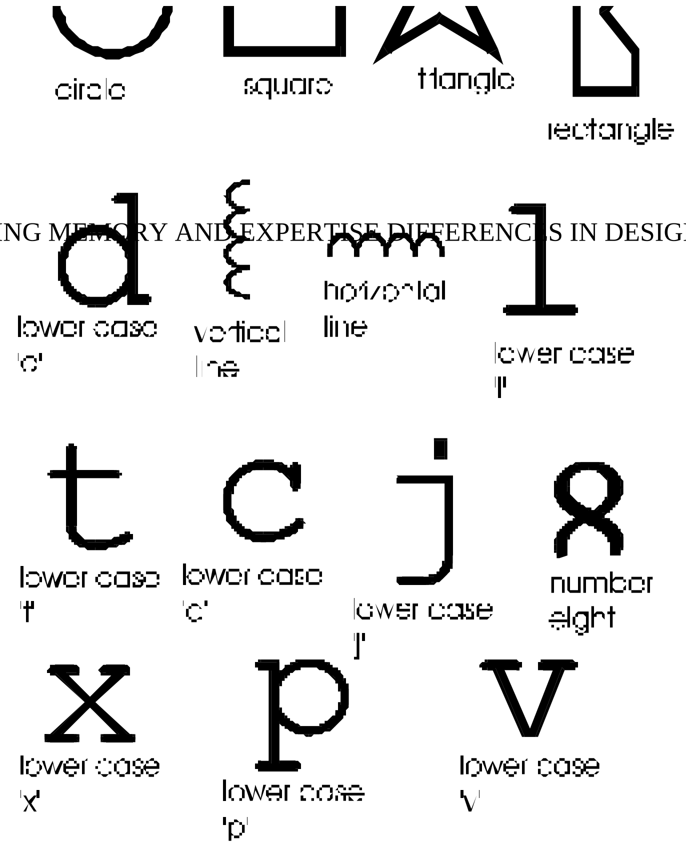

Figure 3. The modified stimuli set used in the experiment.

These items were based on the symbols reported by Finke and Slayton (1988), but were modified so as to increase their complexity and also reduce the strength of correspondence between the labels and symbols. Participants were asked to complete an initial training session in which they learnt the symbols until they could reproduce them from memory in response to the verbal labels. It was emphasised that the symbols had always to be imaged or drawn exactly as initially presented; e.g., if the ‘d’ was being used then all of the characteristics of the font would have to be preserved. Examples of synthesised patterns produced using the modified symbols are given in Figure 4.

The rest of the procedure followed that reported by Pearson et al. (1999). Participants were given up to 90 seconds to produce a pattern once the symbols had been presented to them verbally. They were allowed to manipulate the symbols in any way they wished provided that they did not distort them or substitute other symbols (i.e., using a normal square rather than the correct modified symbol). At the end of the construction period they either wrote down the name of their pattern or ‘no pattern’ if they had been unable to think of anything. It was only after recording the title that participants were allowed to draw the pattern, to try and ensure that any discoveries made were not from the drawing itself in the imagery-alone condition (see Pearson et al., 1996).

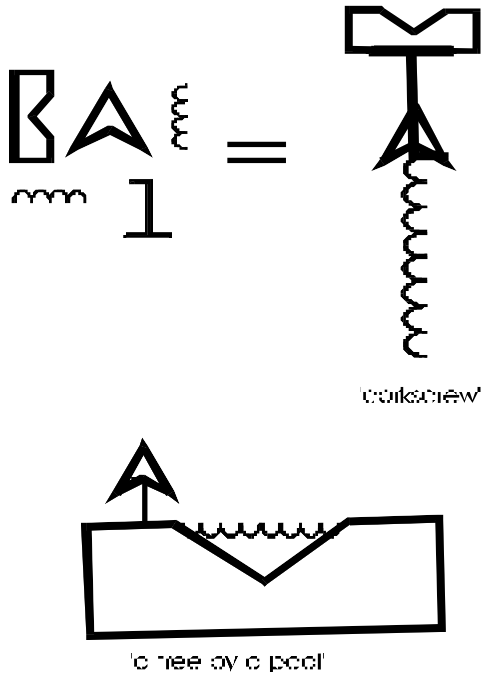

Figure 4. Examples of patterns produced using the modified stimuli set.

Finally, all synthesis trials in the sketching condition were recorded onto videotape. This was done to allow a comparison of the amount of time spent sketching by the novice and expert groups.

2:1 SCORING PROCEDURES

Only legitimate patterns produced by participants were considered for analysis. Patterns were classified as illegitimate if they (a) had not been given a name (b) did not use all five of the presented symbols (c) had modified the symbols or substituted ones that had not been presented.

All of the legitimate patterns were rated by two independent judges who were blind both to the experimental hypothesis and to the conditions under which the patterns had been produced. Each judge was asked to rate every pattern on (a) the correspondence between the assigned name and pattern itself (b) the creativity of the synthesised pattern (c) the quality of the drawing itself. Ratings were carried out on a five-point scale in which 1 was “very poor” and 5 was “very good”. These rating procedures were included so as to provide a subjective assessment of participants’ performance in addition to the objective measurements. The reliability of the ratings was estimated by correlating the performance of the two judges.

In addition to the above, all of the legitimate patterns were assigned a transformational complexity score by the first two authors based on the measure developed by Anderson and Helstrup (1993). This measure counts the number of transformations of each component that were required in order to produce the generated pattern. The collective TC measure equals the sum of scores on four constituents: Size Differences, Rotation, Mirror Imaging and Embedding. The maximum possible TC score for any given pattern was 21.

Finally, the video recordings of the sketching sessions were used to calculate the mean percentage of time spent sketching by the novice and expert groups. This was calculated for the period when the verbal labels were first presented to when either a pattern had been produced or when the 90 seconds had elapsed.

3. Results

In terms of productivity, both the expert and novice groups produced more legitimate patterns when they were allowed to sketch ($F(1,30)=42.68$; $p<0.0001$). The expert group also produced more legitimate patterns than the novices ($F(1,30)=11.77$; $p<0.05$) both in the imagery-alone and sketching conditions, with no interaction. Analysis of the video recordings of participants' behavior in the sketching condition found that both the novice and expert groups spent around 75% of the time sketching during the construction period, with almost no difference at all between the two groups ($F<1$).

For the judges' ratings of the legitimate patterns inter-rater reliability was 0.83 for the imagery-alone condition and 0.72 for the sketching condition (both $p<0.001$). These were sufficiently high to warrant further analysis of the mean rating scores. There was a marginal difference between the groups on the creativity ratings, with experts rated as being slightly more creative than novices ($F(1,28)=3.98$; $p<0.056$).The expert group had significantly better correspondence ratings than the novices ($F(1,28)=5.06$; $p<0.05$). There was also a marginal interaction between correspondence ratings and sketching, in which experts ratings decreased under sketching while novices showed a slight increase ($F(1,28)=3.97$; $p<0.056$). Finally, the experts were judged to have produced clearly better quality drawings than the novices in both the imagery-alone and sketching conditions ($F(1,28)=9.16$; $p<0.005$).

Analysis of the Transformational Complexity scores for the different conditions revealed a significant interaction between expertise and the presence of external support (F(1,28)=5.95; p<0.05). These results are shown in Figure 5. The mean TC scores of the expert group increased when they were allowed to sketch during the synthesis task, while the novice groups' mean TC scores *decreased* when sketching was made available to them.

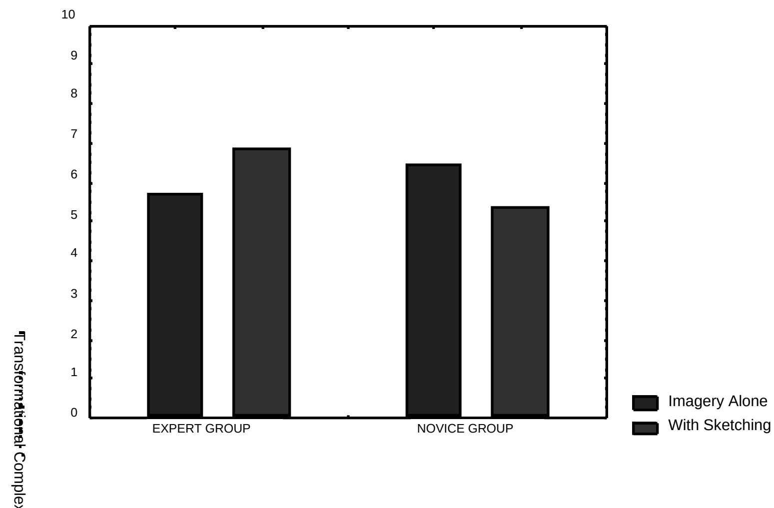

Figure 5. Differential effect of drawing support on the mean transformational scores of novice and expert sketchers.

Following on from the work of Verstijnen et al. (1998b), it was decided to analyse transformational complexity separately for restructuring (size differences and embedding) and non-restructuring (rotation and mirror imaging) transformations. These results are shown separately in Figures 6 and 7. Analysis by two-way ANOVA revealed that only the restructuring variables displayed a significant interaction (F(1,28)=5.19; p<0.05), with the interaction for non-restructuring failing to reach significance (p=0.14). However, the overall pattern of means was the same for both components, with no evidence for any opposing trends.

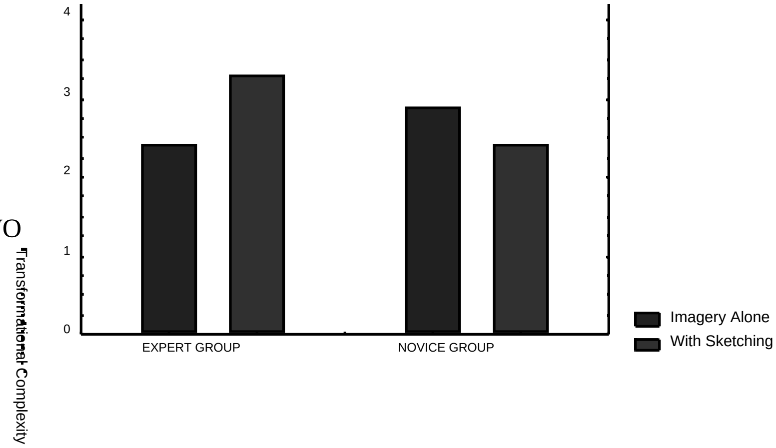

Figure 6. Differential effect of drawing support on measures of non-structuring transformations for novice and expert sketchers.

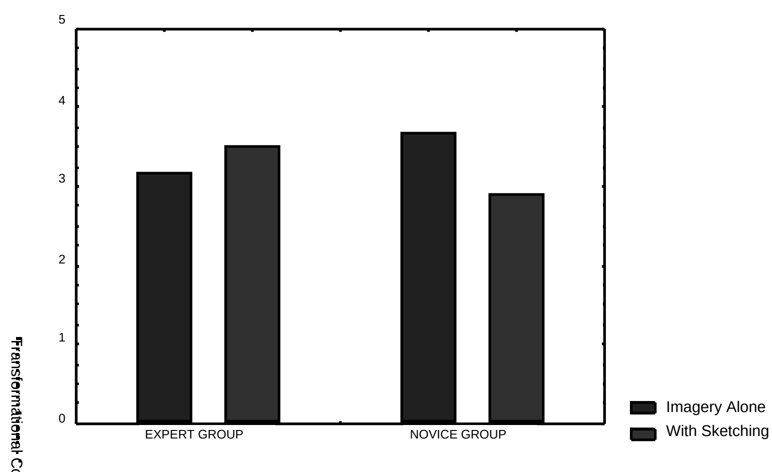

Figure 7. Differential effect of drawing support on measures of restructuring transformations for novice and expert sketchers.

4. Discussion

In contrast to previous studies this experiment found a clear increase in the mean transformational complexity of patterns produced by experts when they were allowed to use sketching during creative synthesis. This suggests that the modified stimuli set used in place of the original Finke and Slayton stimuli was successful in increasing the range of potential transformations available to participants, and also in increasing the load on the visuo-spatial components of working memory.

One initial explanation for this result could be that experts were simply employing sketching to a greater extent that the novices during the construction phase of the synthesis task. However, this explanation can be ruled out because of the analysis of the video recordings, which showed that both groups were sketching for around 75% of the construction period on average. Therefore any difference in performance must be due to the *way* in which the experts were using external support rather than just the frequency. Verstijnen at al. (1998) have suggested that experts rely on sketching only when they need to carry out some form of restructuring transformation such as changing a symbols size or embedding one symbol into another. However, the results of the present study provide limited support for this hypothesis. Although restructuring transformations provided a more reliable effect than the non-restructuring transformations, the overall pattern of means between the two groups was the same. There was no indication of an opposing trend as suggested by Verstijnen et al. In general the main finding was that *all* forms of symbol transformation seemed to increase in the expert group when they were allowed to sketch. In contrast, there is a suggestion that the novice group were actually *inhibited* in carrying out symbol transformations when they were allowed to sketch compared to when they were just using imagery on its own.

One potential explanation for this finding is that it reflects differences between the two groups in terms of how they use working memory as an interface between internally-generated mental images and the external representations they create via sketching. Figure 8 displays a multi-component model of working memory in which the visuo-spatial sketchpad comprises two independent visual and spatial storage systems that interact with a visual buffer where conscious visual images are generated, maintained and manipulated (from Pearson, in press). It is assumed that during creative synthesis participants generate images of the presented symbols in the buffer using verbal labels held in the phonological loop. Once these images have been generated they can be maintained by the activity of the central executive, but this will place considerable demands on general attentional resources. The images can be transformed in the buffer by the operation of the spatial “inner scribe” component, while the visual cache can act as a back-up store for the buffer by maintaining information that is currently outwith conscious imagery. For instance, a participant might be attempting to synthesis the components ‘triangle, square and circle’ into a church tower, but then abandon this approach in favour of an alternative pattern. Although the visual image of the three symbols combined as a church tower would no longer be represented within the visual buffer, sufficient information would be retained in the visual cache to allow for it to be regenerated back into the buffer at a later stage if required.

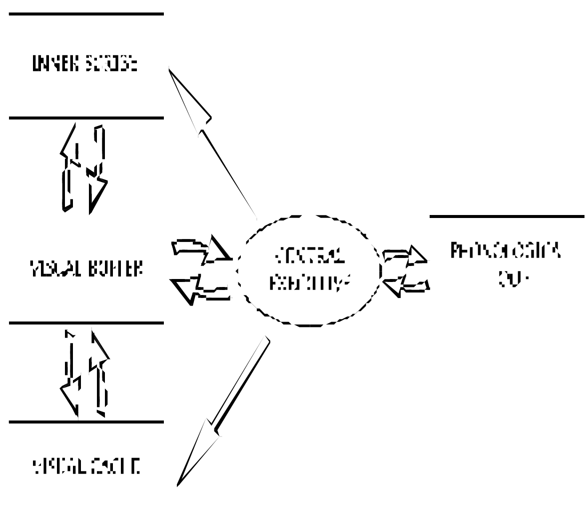

Figure 8. A Visual Cache-Visual Buffer model of VSWM (from Pearson, in press)

During synthesis sketching functions as an external memory which reduces the load on the different working memory systems. Crucially, however this needs to be a *two-way* process if the maximum benefit of using the external support is to be gained. Although the visual images provide the basis for creating the external representations, ideally these representations should then stimulate further mental transformations of the images that then lead on to further sketching. This is likely to be the point at which the architecture students’ expertise in using drawing was most relevant, as they seemed more able to use sketching as a means to increase transformational complexity of their patterns. In contrast the novice group appeared to rely more on sketching as a simple memory aid. While the total number of legitimate patterns they produced increased, there was no gain in transformational complexity. Instead, the results suggest that sketching may have produced an inhibitory effect. Once novices had sketched their ideas the presence of an external representation appeared to discourage further transformations from being carried out in contrast to the imagery-alone condition.

A potential caveat to this interpretation is that the two groups of participants may differ in their general visuo-spatial ability rather than just in expertise in drawing. It is possible that people who are attracted to courses in architectural design have naturally better visuo-spatial ability than those who choose to do non-design oriented courses. However, while Verstijnen et al (1998b) reported differences between experts and novices on a measure of spatial ability (mental paper folding), they argued that this could not account for their reported expertise effects. To explore this issue further on-going research being carried out by the authors is examining performance of the Finke and Slayton synthesis task by students in different years of an architecture course. These results should help clarify further how changes in performance on the task may be linked to increases in expertise in using sketching to facilitate the design process.

4.1. CONCLUSION

Previous studies using the creative synthesis procedure devised by Finke and Slayton (1988) have either failed to find any beneficial effect of external support (Anderson & Helstrup, 1993), or else found that any benefits are restricted to certain types of mental transformation (Verstijnen et al., 1998b). This paper has argued that these results may result from specific characteristics of the original stimuli set, and that by substituting modified symbols it is possible to produce a significant general increase in transformational complexity within an expert group when they are allowed to make use of external support. Architecture students were able to make more interactive use of sketching during creative synthesis than a comparable novice group, who instead appeared to rely on sketching mainly as a simple memory aid.

Acknowledgements

We would like to thank staff at the RGU Scott Sutherland School of Architecture for their assistance during the completion of this study.

References

Anderson, R.E. & Helstrup, T. (1993). Visual discovery in mind and on paper. *Memory and Cognition,* **21**, 283-293.

Baddeley, A.D. (1986). *Working memory*. Oxford: Oxford University Press.

Baddeley, A.D., & Lewis, V.J. (1981). Inner active processes in reading: The inner voice, the inner ear and the inner eye. In A.M. Lesgold & C.A. Perfetti (Eds.), *Interactive processes in reading*,. LEA: Hillsdale, NJ. pp. 107-129.

Barquero, B. & Logie, R.H. (1999). Imagery constraints on quantitative and qualitative aspects of mental synthesis. *European Journal of Cognitive Psychology,* **11(3)**, 315-333.

Chambers, D., & Reisberg, D. (1992). What an image depicts depends on what an image means. *Cognitive Psychology,* **24**, 145-174.

Finke, R. (1990). Creative imagery: Discoveries and inventions in visualization. Hillsdale, NJ: Lawrence Erlbaum.

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

Goldschmidt, G. (1991). The dialectics of sketching. *Design Studies,* **4**, 123-143.

Gross, M.D., Ervin, S.M., Anderson, J.A. & Fleischer, A. (1988). Constraints: knowledge representation in design. *Design Studies,* **9(3)**, 133-143.

Herbert, D.M. (1988). Study drawings in architectural design: their properties as a graphic medium. *Journal of Architectural Education,* **41(2)**, 26-38.

Logie, R.H. (1995). *Visuo-spatial working memory*. LEA:Hove.

Miyake, A. & Shah, P. (1999). Towards unified theories of working memory: Emerging general consensus, unresolved theoretical issues, and future research directions. In A. Miyake and P. Shah (Eds.), *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control.* Cambridge University Press: New York. pp. 442-482.

Pearson, D.G. (in press). Imagery and the visuo-spatial sketchpad. In J. Andrade (Ed.), *Working Memory: New Applications and Advances in Theory.* Hove: The Psychology Press.

Pearson, D.G., Alexander, C., Rockenbach, C., & Webster, R. (in prep.) *The role of working memory and drawing support in expertise differences in creative visual design.*

Pearson, D.G. & Logie, R.H. (2000). Working memory and mental synthesis. In S. O'Nuallain (Ed.), *Spatial Cognition: Foundations and Applications.* John Benjamins Publishing Company: Amsterdam. pp. 347-359.

Pearson, D.G., Logie, R.H., & Gilhooly, K. (1999). Verbal representations and spatial manipulation during mental synthesis. *European Journal of Cognitive Psychology,* **11(3**), 295-314.

Pearson, D.G., Logie, R.H., & Green, C. (1996). Mental manipulation, visual working memory, and executive processes. *Psychologische Beitrage,* **38**, 324-342.

Purcell, A.T. & Geno, J.S. (1998). Drawings and the design process. *Design Studies,* **19(4)**, 389-430.

Reisberg, D. (1996). The nonambiguity of mental images. In C. Cornoldi, R.H. Logie, M.A. Brandimonte, G. Kaufmann, and D. Reisberg (Ed.), *Stretching the imagination: Representation and transformation in mental imagery.* New York: Oxford University Press. pp. 119-172.

Reisberg, D. & Heuer, F. (in press). Visuospatial images. In P. Shah and A. Miyake (Eds.), *Handbook of Visuospatial Thinking.* Cambridge University Press: New York.

Reisberg, D., & Logie, R.H. (1993). The ins and outs of visual working memory: Overcoming the limits on learning from imagery, In M. Intons-Peterson, B. Roskos-Ewoldsen, & R. Anderson (Eds.), *Imagery, creativity, and discovery: A cognitive approach.* Amsterdam: Elsevier. pp. 39-76.

Verstijnen, I.M., van Leeuwen, C., Goldschimdt, G., Haeml, R., & Hennessey, J.M. (1998a). Sketching and creative discovery. *Design Studies,* **19(4)**, 519-546.

Verstijnen, I.M., van Leeuwen, C., Goldschimdt, G., Haeml, R., & Hennessey, J.M. (1998b). Creative discovery in imagery and perception: Combining is relatively easy, restructuring takes a sketch. *Acta Psychologica,* **99**, 177-200.