IDEAS, THE EMBODIMENT OF IDEAS, AND DRAWING: AN EXPERIMENTAL INVESTIGATION OF INVENTING

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Abstract. The term *visual reasoning*, in cognitive psychology, often refers to the use of visual spatial relations in making inferences about corresponding conceptual relations. The conclusion is that external visual representations have special properties, which can aid reasoning about higher order abstract concepts. The design literature is more specific and often sees visual reasoning as synonymous with drawing, and considers this a core activity in resolving design problems. The research to be reported examined visual reasoning and design, by investigating the role that drawing plays in the practicality and creativity of inventions. The most striking finding was that using only mental imagery produced more creative and practical inventions than the use of drawing and that this was dependant on the area of expertise of the participants. This appears to run counter to the views found in both the visual reasoning and design literature regarding the effectiveness of visual representations and drawing. This has implications for our understanding of both the visual reasoning and design thinking processes.

1. Introduction

Design is a problem solving activity, and like all such activities requires reasoning. Literature concerning the design reasoning process (for example see Do and Gross (1996)) discusses the reliance, by designers, on the use of drawing to aid conceptualisations and design reasoning. As drawing is a visual medium, design reasoning can be considered synonymous with visual reasoning in that designers may use drawing as a vehicle for reasoning. Drawing is

considered by Herbert (1993) to be a designer's principle means of thinking. In a sense the views of the design literature parallel the views of the cognitive psychology literature concerned with visual reasoning. Essentially the cognitive psychology literature (for example see Gattis and Holyoak (1996)) views visual reasoning as the use of visual spatial relations in making inferences about corresponding conceptual relations, concluding that external visual representations have special properties which can aid reasoning about higher order abstract concepts. The parallel rests in the notion that the design process is seen as one in which designers visually reason internally via mental imagery, then draw generating external representations of that imagery, reflect and reason about the external imagery, then draw again. This symbiotic relationship between the internal visual imagery and the external visual imagery to reason to a solution is seen as a systematic dialectic between the two modes of reasoning (see Goldschmidt (1991)). The problems designers reason through to resolution are generally ill defined, which generally means there is more than one way in which to resolve the problem. Hence creativity in solution development plays as much a part in the design thinking process as the reasoning process. The act of invention typifies this creative yet reasoned approach to problem solving. However, in the main the visual reasoning research found in the cognitive psychology literature empirically investigates well-defined problems, which have one solution (i.e. solving a physics problem).

Research concerning visual reasoning found in the cognitive psychology literature largely uses empirical methods; conversely the design research literature tends to contain anecdotal evidence which is largely based on designer's thinking and speculating about the design process on the basis of their own experiences. While the initial reason for the research to be presented was to investigate issues revolving around creative mental synthesis and drawing, it is no less important to the visual reasoning research in that it empirically examines the role of drawing in creating and developing practical inventions. As the act of inventing involves creativity and reasoning about spatial relationships, resulting in three-dimensional artefacts, which serve some purpose, it directly relates to both the design and visual reasoning research.

2. Cognitive Perspective

The cognitive research focusing on visual reasoning (see for example, Gattis and Holyoak (1996); Larkin and Simon (1987); Larkin (1983); Tabachneck et. al. (1994); Kindfield (1992) Anazi and Yokoyama (1984)) has some common themes. Whether the authors are writing about resolving physics problems, economics problems, or biology problems the overarching theme is that diagrams can, and often do, play a significant role in reasoning through problems. Across these quite varied domains, in general, the problem solvers

signer's principle means of dentify the underlying nature and structure of the problem 2) generate
ure parallel the views of thitions of the problems (i.e. Diagrams) to aid solution discovery, 3)
ual reasoning. Essentially thrences from these representations which lead to a resolution of the
iattis and Holyoak (1996)) vThese three aspects of reasoning through a problem are also generally
relations in making infereinterdependent. Essentially abstract knowledge and drawings are
concluding that extern mutually influence each other. They are thought to be co-dependent,
which can aid reasoning afield (1992) argues conceptual knowledge and diagrams co-evolve.
s in the notion that the desidies are significant to design in that their core themes are not unlike
reason internally via mentnd in design literature (see for example Lawson (1980); Goldschmidt
tations of that imagery, rchon and Wiggins (1992)). It should be noted, however, that some
aw again. This symbiotic reasoning research, which focuses on mechanical problems (see for
e ernal visual imagery tc Hegarty and Just (1993); Hegarty and Sims (1994)), closely parallels
between the two modes ofroblems, in contrast to the economics problems of Tabachneck et.al.
esigners reason through to While initially, these empirical studies appear to be best placed to
neans there is more than o visual reasoning research in the design domain beyond the anecdotal
ivity in solution developn generally offered, they also have another common attribute. They
ss as the reasoning procesy use problems having only one acceptable solution, whereas design
oned approach to problens are often vague and ill defined having more than one acceptable
g research found in the , as discussed previously.
ites well-defined problerie visual reasoning research tasks are generally solution specific, other
lem).   ι in cognitive psychology, while remaining empirical in nature,
ound in the cognitive psges acceptable multiple solutions. This research methodology (see for
conversely the design Finke and Slayton (1988); Finke (1990)) explored what is termed
nce which is largely ł mental synthesis. They claimed that the previous work in mental
ie design process on theis (with mental synthesis defined as the ability to imagine new forms
n for the research to be from component forms) restricted the subjects to essentially a solution
l ative mental synth problem. The subjects (see for example Thompson and Klatzy (1978))
ial reasoning research ixpected to generate a predetermined form. What sets the work of Finke
reating and developing ayton (1988) and Finke (1990) apart from previous work is the central
creativity and reasonir visual "discoveries" in imagery. Finke and Slayton (1988) investigated
onal artefacts, which sere mental synthesis of 2D forms; Finke (1990) sought to extend the
d visual reasoning reseaxh by investigating 3D forms via invention development. He felt the flat
mensional forms to be of little practical value to three-dimensional
rs such as engineers or inventors.
sentially the subjects were shown drawings of fifteen *basic* forms. For
le in Finke (1990) 3D forms were used (e.g. sphere, cone, cylinder,
oning (see for examplegular block). From the set of fifteen forms, three forms were randomly
Larkin (1983); Tabached and named for the subjects in each trial of a set of trials. In addition to
ma (1984)) has some cree named parts the subjects were given an invention category (e.g. Toys
resolving physics prtames – Furniture – Appliances etc....). As soon as the parts and category
overarching theme named the subjects had to close their eyes then were given a short time to
it role in reasoning ally assemble the parts to make some kind of useful (practical) object. At
general, the problem

the end of the time period they were instructed to open their eyes and write down the name of the practical object, then draw it and then describe it.

2.1. THE ROLE OF DRAWING IN INVENTION

While the creative mental synthesis research above has a drawing component, drawing is not seen as an aid in the development of either the recognizable forms or the practical inventions. However, the research of Anderson and Helstrup (1993) had investigated whether allowing subjects to draw while they were performing the task, affected performance. It was argued that developing an object by performing this task mentally might involve a high cognitive load and that drawing while thinking and developing a solution may lighten the cognitive load by externally representing the form being worked with. In order to test the importance of drawing in creative mental synthesis Anderson and Helstrup (1993) conducted experiments modelled after Finke and Slayton (1988). The subjects, in Anderson and Helstrup (1993), in some trials were encouraged to draw while developing their forms, and other trials they were instructed to develop the forms only mentally. Anderson and Helstrup (1993) found no difference between using only internal visual imagery and using external visual imagery (that is drawing with pencil and paper) as support for generating patterns of good correspondence. Additionally, there was no difference in the number of creative patterns generated either using pencil and paper support to develop the forms or only mentally developing the forms. This research appears to parallel both the visual reasoning research and the design research in that the subjects were encouraged to use drawing to develop their ideas but the results appear to be counter to both the visual reasoning research and design beliefs.

However, Kokotovich and Purcell (2000) argued that the Anderson and Helstrup (1993) results did not constitute an appropriate test of the design belief that drawing is important in creative design for two reasons. First the participants in Anderson and Helstrup (1993) did not come from a design background and consequently might not have the required skill in using drawing in this way. Second the participants in their research were simply encouraged to draw while developing their ideas without being told how to use drawing, which does not necessarily parallel how drawing is used in design. Kokotovich and Purcell (2000) argued the structure of the creative mental synthesis task allows a much more careful analysis of drawing by controlling, quite explicitly, when the drawing activity occurs while conceptualising and developing the idea for an invention. The data they reported appeared to demonstrate that none of the ways in which drawing could be used increased the creativity of the inventions produced. Rather creativity was enhanced when ideas for inventions had to be developed using only mental imagery. Further the extent to which creativity was enhanced depended on the way in which the

participant was presented with the problem and on whether or not the participant was a designer and the particular design discipline involved.

The focus of Kokotovich and Purcell (2000) was on the issue of drawing and creativity in design and their results again appear to be inconsistent with design beliefs about creativity. The visual reasoning research has not addressed the issue of creativity in problem solving and so it could be argued their results are not relevant to visual reasoning. It can also be argued that being able to produce a practical invention is relevant to visual reasoning as it can be conceptualised as a successful resolution of the problem. In the creative mental synthesis task, the inventions produced are judged in terms of both their creativity and their practicality and both types of judgements were obtained as part of the data that formed the basis of the Kokotovich and Purcell (2000) paper on creativity and drawing. Given that practicality is closer to the usual visual reasoning research this paper analyses the practicality data from a visual reasoning perspective. However it can be argued that a creative solution represents a particularly successful outcome and is consequently also relevant to visual reasoning. This paper therefore includes the creativity data reported in Kokotovich and Purcell (2000) to allow a comparison between the two in the context of visual reasoning.

3. The Experiment

3.1. EXPPERIMENTAL METHODS

In order to investigate specific themes relating to how and when drawing may be used to develop inventions, Kokotovich and Purcell (2000) developed a series of tasks, which were divided into four distinct strategies (note in Table 1 below the different strategies (Strategies ABCD)), and two distinct phases within each strategy (note in table 1 below Tasks 1 and 2). The participants in the experiment were senior industrial and graphic design students representing two different types of designer and similar senior students in law representing a non-design group. Groups of 20 from each background participated in the experiment.

In all the Task 1 phases their subjects completed three trials lasting three minutes each. When completing Task 2 phases, in order to maintain consistency between tasks, the subjects were given nine minutes to complete the tasks. The nine minutes relates to the time allowed in the Task one phase (3 trials x 3 minutes each). In order to maximize the creative output, in all tasks the subjects could create as many forms as they liked before the end of the time period.

TABLE 1. Strategy type and Task type.

Drawing Strategies and Invention			
Strategy A	**Strategy B**	**Strategy C**	**Strategy D**
<u>Task 1</u>	<u>Task 1</u>	<u>Task 1</u>	<u>Task 1</u>
Using drawing to develop ideas (time limit)	Using mental imagery to develop ideas (time limit), then draw the ideas (no time limit)	Using drawing to develop ideas (time limit)	Mentally develop and name forms (time limit) (no parts given), THEN parts given to develop the previously named forms (no time limit)
<u>Task 2</u>	<u>Task 2</u>	<u>Task 2</u>	<u>Task 2</u>
Using drawing to rotate and reinterpret forms (time limit)	Using drawing to rotate and reinterpret forms (time limit)	Using mental imagery alone to rotate forms then draw and reinterpret forms (time limit)	Using drawing to rotate and reinterpret forms (time limit)

(Phase 1 / Phase 2 labels in left margin)

In the first phase (task one) of Strategy A and Strategy C (see Table 1 above) the subjects were instructed to draw while they developed a practical invention. With the exception of being told to use drawing to develop the invention instead of closing their eyes and using only 'mental imagery', the procedures were similar to those of Finke (1990).

In Task 2 of Strategy A, Strategy B and Strategy D (see Table 1 above), after having completed all three trials, in Task 1, the subjects were to use drawing to reinterpret their ideas from task one by sketching the previous forms in new orientations. They were not allowed to reconstruct their previous inventions, they were only to rotate, slide and/or scale all or some of the parts of their inventions in order to reinterpret them.

In the initial phase (Task one) of Strategy B (refer to Table 1 above) the subjects were instructed to develop a practical invention via 'mental imagery' only as in Finke (1990).

In Task 2 of Strategy C (see Table 1 above), the subjects were to reinterpret the ideas and drawings from Task 1 of Strategy C by selecting one of the ideas then closing their eyes and mentally reinterpreting it. The instructions for reinterpretation here, were identical to those of the other second phases in the other strategies, with the exception they were to do this by only mentally

manipulating the forms. If they had a reinterpretation they were to open their eyes write the idea down, then describe and draw it.

They could repeat the procedure in order to create as many inventions as time would allow.

Task 1 of Strategy D was divided into two parts. Initially the subjects closed their eyes and were required to mentally develop an invention within a given category without being given the parts. Once the subject had an idea they were to open their eyes write it down, then if time had not run out they closed their eyes again and were to develop another idea. Next they were given a triplet of parts for each trial and they had to use these parts to embody their ideas, via drawing.

Student judges (15 in total), equally represented from the three different disciplines (Industrial designers, Visual communication designers, and Non-designers), reviewed the resultant drawings making creativity judgments and practicality judgments, using a scale of 1 to 5 (1 being the lowest and 5 being the highest). If a majority of judges gave an invention a score of 4 or better it was counted as creative and if a majority of judges gave an invention a score of 4 or better for practicality it was considered practical. The judges were blind to both who developed the individual responses, and the drawing strategy conditions as they were reviewing the randomly ordered responses. (For the details of the experimental methods and procedures see Kokotovich and Purcell (2000)).

3.2. EXPECTATIONS OF DRAWING

In the previous section we outlined the different drawing strategies and tasks, which were controlled in order to investigate drawing issues while the subjects endeavoured to conceptualise and develop inventions. The following is a discussion of the expected results of these manipulations from both a visual reasoning and design perspective, Strategy by Strategy.

Given that both the visual reasoning literature and the design literature argue that external visual representations (drawing) and internal conceptualisations and reasoning are co-dependent in order to resolve visual problems, it would be expected that both Strategy A Task 1(drawing to develop ideas and solve problems) and Strategy A task 2 (drawing to reinterpret ideas) should yield the highest frequency of practical inventions and creative inventions. In addition, the second tasks (Task 2) of Strategies A,B&D, based on the design literature's arguments of emergence in drawings, should also yield a high number of practical and creative inventions. That is in all of the conditions where drawing was permitted there should be increases in creativity and practicality of the inventions produced.

However, based on the findings of Anderson and Helstrup (1993) there should be no difference in either the frequency of practical inventions or

creative inventions when comparing Strategy A Task 1(drawing to develop ideas and solve problems) and Strategy B Task 1 (only mentally developing ideas and solving problems). This is in direct conflict with both the visual reasoning literature and design literature, given that both the visual reasoning literature and the design literature argue that drawing aids internal conceptualisations and visual reasoning. It would be a reasonable expectation that the use of drawing to develop practical inventions in lieu of solely using mental imagery would lead to increased numbers of practical inventions. This is seen as plausible, given the consistency of the existing literature, which suggests a strong symbiotic relationship between drawing, visual reasoning, and creative mental synthesis.

In order to test the possibility that mentally reinterpreting inventions may be as effective as drawing to develop inventions, Strategy C Task2 (mentally reinterpreting inventions) was included. If mentally developing and reinterpreting inventions is an equally acceptable strategy as using drawing to reinterpret inventions, then mentally reinterpreting inventions should yield similar frequencies of practical and creative inventions when compared to the other Task 2 strategies.

When researching expert and novice designers, Mathias (1993) found novice designers often use drawing to focus early on a design solution. In contrast, experts would use drawing to generate ideas and concepts (not unlike the views argued in the visual reasoning literature) and not form at this stage of the process. In operating at the level of abstract ideas and concepts experts appear to develop a complex search space opening up the possibility of innovative and creative outcomes. In the later stages of the design process, Mathias (1993) found that expert designers use drawing and modelling for synthesis to embody the ideas in physical form (again quite similar to the views argued in the visual reasoning literature). As experts tend to separate ideas from the embodiment of ideas then use drawing to develop the ideas, an expectation would be that increased numbers of practical ideas would be developed through the use of drawing as an aid to the visual reasoning process. In addition, consistent with the design literature, increased numbers of creative inventions would be expected when using Strategy D Task 1.

3.3. DATA AND ANALYSIS

Tables 2 and 3, below, show the relationship between frequency of practical and creative responses and various drawing strategies and tasks in tabular form. Table 2, below, shows the frequency of creative inventions, while Table 3 shows the frequency of practical inventions. Each row represents a subject type, and each column a Strategy/Task type, allowing comparisons and contrasts between subject type and strategy type to be made.

A striking result, apparent in Table 2 below, is that Strategy D Task 1 (separating ideas from the embodiment of ideas) has the greatest frequency of creative responses (155 in total) from all subject types.

TABLE 2. Number of creative responses attributed to subject type, strategy type and task.

	Drawing Strategies and Subject Types (Creativity 3D) (all judges)								
	Strategy A Task 1	Strategy A Task 2	Strategy B Task 1	Strategy B Task 2	Strategy C Task 1	Strategy C Task 2	Strategy D Task 1	Strategy D Task 2	Total Creative
Industrial Designers	15	12	36	13	13	11	70	10	180
Vis - Com (Students)	9	8	18	5	10	5	59	7	121
Non-designers (Law students)	2	0	5	3	2	0	26	2	40
Total Creative	26	20	59	21	25	16	155	19	341

However, in contrast Strategy D Task 1, in Table 3 below, yielded the lowest frequency of practical responses (9 in total) from all subject types. In one sense this is a surprising result, however, it appears to be consistent with Mathias (1993) regarding the tendency of expert designers to separate ideas from the embodiment of ideas, and redefine the brief. Equally surprising, in contrast however, is the finding that this strategy of the separation of ideas from the embodiment of ideas results in a severe drop in practical ideas.

TABLE 3. Number of practical responses attributed to subject type, strategy type and task .

	Drawing Strategies and Subject Types (Practicality 3D) (all judges)								
	Strategy A Task 1	Strategy A Task 2	Strategy B Task 1	Strategy B Task 2	Strategy C Task 1	Strategy C Task 2	Strategy D Task 1	Strategy D Task 2	Total Practicality
Industrial Designers	10	12	40	17	14	12	6	19	130
Vis - Com (Students)	11	9	11	6	5	12	2	10	66
Non-designers (Law students)	4	5	12	5	18	13	1	7	65
Total Practical	25	26	63	28	37	37	9	36	261

In addition, it is clear, in Tables 2 and 3 above, the overall totals for Strategy B Task 1 (Mentally developing inventions) were more than double those of Strategy A Task 1 (Drawing to develop inventions) in terms of both practicality and creativity. When comparing the frequencies of creative inventions in Table 2, Strategy B Task 1 had a total of 59 creative inventions, were as a total 26 creative inventions were developed using Strategy A Task 1. In Table 3, in

terms of the frequency of practical inventions, Strategy B Task 1 totalled 63, were as there was a total of 25 practical inventions developed using Strategy A Task 1 (Drawing to develop inventions).

While visual reasoning is considered a generalized activity, by virtue of their training in the use of drawing for the conceptualisation and development of solutions to three-dimensional problems, the industrial designer, in particular, could be expected to have increased frequencies of creative and practical inventions when using Strategy A Task 1 (Drawing to develop inventions). However, this was not the case. As shown in Table 2 above, the Industrial designers were able to develop two and one half times more creative inventions when using Strategy B Task 1 (Mentally developing inventions) a total of 36, in contrast to Strategy A Task 1 (Drawing to develop inventions) a total of 15 creative inventions. When reviewing the frequencies of practical inventions generated by the industrial designers, in Table 3 above, they were the only group able to develop a four-fold increase in practical inventions when using Strategy B Task 1 (Mentally developing inventions) a total of 40, in contrast to Strategy A Task 1 (Drawing to develop inventions) a total of 10 practical inventions.

In general, given the frequencies of Strategy A Task 1 and Task 2, in Tables 2 and 3 above, when either using drawing as an aid in developing inventions (Task 1) or reinterpreting inventions (Task 2), the frequencies of practical inventions and creative inventions remain relatively low. Given the views of both the visual reasoning and design literature regarding the co dependence of internal conceptualisations and external representations (drawing) in the resolution of problems, these findings appear to run counter to the expectations discussed earlier. The use of drawing should have aided invention conceptualisation and development.

4. Conclusion

As discussed earlier, a common theme running though both the visual reasoning literature and the design literature is that the act of drawing aids conceptualisation and reasoning. Other literature (see Anderson and Helstrup (1993)) suggested the act of drawing is of little consequence. However, as we discussed earlier, in their work, they did not use subjects from a design background, who are trained in how to use drawings to solve problems. In addition, their subjects were not instructed in how to use drawing to resolve the problems. In Anderson and Helstrup (1993), the subjects were merely told to 'doodle'.

Contrary to expectations discussed earlier, and the views of both the visual reasoning and design literature, the results of this study reveal that mentally conceptualising and developing inventions is more effective than using drawing

as an aid. The data, described earlier, revealed that when using only mental imagery to develop ideas, then using drawing to embody those ideas (as in Strategy D Task 1), substantial increases in creative invention can and does occur.

Further support in using only mental imagery to conceptualise and develop inventions can be demonstrated by the fact that 3D designers using Strategy B Task 1 (mentally developing inventions) were able to quadruple the number practical inventions, compared to when they used Strategy A Task 1 (Drawing to develop inventions). In addition they were able to more than double the frequency of creative inventions by only mentally developing their inventions, as opposed to using drawing to develop their inventions. From a visual reasoning perspective, it is possible that mental imagery is being used to access conceptual knowledge that is important and relevant. That is to say the subjects may be visually reasoning in the mind rather than externally via drawings. Therefore, we conclude that mental imagery and mental modelling ('running' and 'playing with' the inventions in the mind) is more potent than generally given credit, at least for 3D designers.

When reviewing the results of Task 2 (Drawing to reinterpret inventions), it can be argued that the subjects were limited or constrained in their emergent inventions. They were not allowed to reconstruct their previous inventions, they were only to rotate, slide and/or scale all or some of the parts of their inventions in order to reinterpret them. Designers are thought to reconstruct or even add and subtract parts to their ideas. Our subjects were restricted in that they were not allowed to do this. Hence, it can be argued we limited their ability to invent. This notwithstanding, the subjects were, in Strategy A task 1, given the freedom to reconstruct their inventions. Therefore, we would argue that increased numbers of creative and practical inventions should have occurred when contrasting Strategy A Task 1 (Drawing to develop inventions) with Strategy A Task 2 (Drawing to reinterpret inventions). The increase did not occur.

These findings appear to run counter to the results of Verstijnen (1997), who also investigated creative mental synthesis and invention using designers and non-designers as subjects. However, it must be remembered that the central issues of her correlation studies, revolved around creativity, drawing, synthesis, and analysis. She differentiated synthesis and analysis by describing synthesis as a figural combination task, and analysis as restructuring with an expectation of emergent forms, linking these to drawing and non-drawing conditions to develop ideas. In addition, for purposes of consistency with respect to Anderson and Helstrup (1993), our work, in contrast to hers, required all the subjects to experience all drawing conditions.

The comparisons made in Verstijnen (1997) between designers and non-designers, in terms of creativity were correlated with synthesis and analysis ratings suggesting that drawing aids analysis, thereby leading to creative

outcomes. Therefore, in relation to our study it should be expected that Strategy A Task 2 (drawing to reinterpret) should yield increased numbers of creative inventions, in contrast to Strategy B Task 1 (mentally developing inventions). This increase did not occur in our work. Alternatively, the possibility exists that drawing for analysis (reinterpreting), may aid in developing practical inventions, this was not teased out of her data. In our data, as indicated earlier, mentally developing inventions, as in Strategy B Task 1, leads to increased practical inventions, in contrast to Strategy A task 2 (drawing to reinterpret inventions).

As our study used elements and tasks close to those a 3D designer would be accustomed to resolving, the 3D designers would be expected to produce outcomes similar to industrial design solutions (innovative and practical). This is part of the reason for the choice of the participants. This research specifically sought to stay close to Finke and Slayton (1988) and Finke (1990). This in turn leads to the work of Anderson and Helstrup (1993) with respect to drawing issues. If we went straight to a design task without doing these experiments, it could be argued that the research and research methods are not related to their work, therefore, we would lose the connection. Given the Finke (1990) tasks and the groups used, there is a sense in which the things they are manipulating in the task have a relationship to the designers. However, the next logical step is to, in some way, develop the Finke and Slayton (1988) and Finke (1990) tasks into a fully-fledged design task and then examine it, thus moving even closer to design issues.

Acknowledging that the tasks, while very similar to design problems, are not exactly design problems, does not diminish the results obtained. In fact while few in number there is some support within both the visual reasoning literature and the design literature suggesting that using mental imagery is more potent than generally revealed. In a sense our findings are not entirely unexpected. In a protocol study Athavankar (1995) blindfolded expert designers, and directed them to evolve their designs exclusively using mental imagery. He suggested there is some evidence to support the view that designers are able to mentally model their designs and with natural ease 'play with it' to resolve design problems. In addition some of his subjects suggested that they were in fact more fluent with ideas and enjoyed working this way (blindfolded).

Within the visual reasoning research there is also some evidence that using only mental imagery, in some instances, is an effective strategy, and perhaps more effective than using drawing. Some theoretical accounts describe the process of inferring the operation of a physical device as envisioning or 'running' a mental model (For example see: de Kleer and Brown (1984); Reiger and Grinsberg (1977); Williams et al (1983); Thurstone (1950)). It is possible the designers in this study are mentally modelling their inventions rather than externally representing them (drawing). This, however, appears to be reliant on mental visual spatial abilities. In Gattis and Holyoak (1996) the

subjects are thought to be 'chunking' visual information to highlight conceptual information. Drawing is thought to aid this process to enable the testing of potential conclusions, based on mental models, to verify if each possible mental model is consistent with the constraints placed on a system. Yet, in an ill-defined problem, like a design problem, the constraints often change. As indicated earlier, designers often define and redefine problems {i.e. act as problem setters} (for example see Mathias (1993)) in addition to solving problems {i.e. acting as problem solvers}. If the design and constraints of the inventions are continually in a state of rapid change, the mental models need to rapidly change as well. The act of drawing may not facilitate the mental conceptualisations and developments. It is possible that designers are able to more readily, 'run' or 'play with' these mental models of their inventions due to their mental visual spatial abilities. That is to say the experienced 3D designers may be visually reasoning internally via the mental models, rather than externally via drawings.

Given the discussion above, 'running' or 'playing with' mental models seems to require mental animation abilities as well as visual spatial abilities in order to visually reason though problems concerning inventions. Often inventions result in a three-dimensional object, which solves a problem. Sometimes these inventions have mechanisms (i.e. parts which move). In order to develop these movable inventions and model how they might work, mental animations may need to occur to test run the inventions to make sure they are practical. In their visual reasoning research, investigating mental animation and mechanical reasoning, Hegarty and Sims (1994) argued mental animation was another cognitive component of mechanical ability. In addition, they argued mental animation in a mechanical visual reasoning task was linked to visual spatial ability. They used low spatial ability and high spatial ability subjects, which were drawn from a general psychology class. Their subjects were to mentally animate mechanical devices (as inventions sometimes have). Errors of understanding, with respect to the motion of the mechanisms, were counted. Hegarty and Sims (1994) had shown only the low spatial ability subjects had increased errors the further down the causal chain in a mechanical problem they progressed. The high spatial ability subjects were largely successful in the mental animation, mechanical reasoning task. In the context of our research, the industrial designers may have done well due to a combination of high spatial, mental animation, and mechanical reasoning abilities. This could account for our finding that the industrial designers did well when using Strategy B Task 1 (mentally developing inventions).

When discussing the issue of mentally developing an invention as opposed to using drawing as an aid, it can be argued that drawing may interfere with processing abilities, not only because of rapidly changing conceptualisations as discussed earlier, but also because of a loss of clarity of an overall concept due to a subject breaking down a concept into 'chunks' they can comprehend.

Returning to the concept of 'chunking', described in the visual reasoning research of Gattis and Holyoak (1996), if the subjects in our study are considered to be 'chunking' the inventions, then 'running' the mental models to verify constraints {investigating corresponding conceptual relations}, as in Strategy B Task 1 (mentally developing inventions), the act of drawing {external visual representations}, as in Strategy A Task 1 (Drawing to develop inventions) may inhibit the subjects. They may be breaking down the conceptualisations in a piecemeal fashion in order to draw it, thus interfering with the clarity of the overall concept. Hegarty and Sims (1994), in their visual reasoning research, argued that subjects might break down the process of mentally animating complex systems (i.e. mentally animating an invention) into the animation of individual components. If this is true, the lack of understanding of the bigger 'picture' may lead to an impractical invention. That is to say, if the subject cannot envisage the whole invention 'running', due to a lack of visual spatial abilities, then practicality issues may remain unresolved. In addition, from a creativity standpoint, drawing may channel the thinking of a subject into only a few directions (the subject may be relying on emergence to occur), causing the search space for solutions to be smaller, thereby limiting creative ideas. Whereas, quickly mentally modelling whole inventions and 'running' them holistically, may allow for an understanding of a greater number of creativity judgments and practicality issues which need to be reviewed/resolved. As Athavanker's subjects put it 'they became more fluent with their ideas' when blindfolded. This is consistent with our findings and Strategy B Task 1 (mentally developing inventions).

The findings of this study have implications for both the design and visual reasoning research, in that when confronted with ill-defined problems mentally conceptualising and reasoning though those types of problems is more beneficial than using drawing in the early phases of the design process, the result expected from the typical view of visual reasoning. However, this is not to say that drawing is not important, just it may be that when drawing is used, is the important factor in visual reasoning.

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PREFACE

Design is the precursor to the construction and production of society's diverse array of artifacts. Artifacts contribute significantly to the quality of the physical, mental, and cultural lives of the members of a society. Given the pervasiveness of artifacts, their design and manufacture have economic as well as cultural importance. Designers are highly trained. Even so, many designs fall short. Increasing the effectiveness of design processes, especially by facilitating innovation, could make significant contributions to the quality of design with consequent effects on quality of life.

For these reasons, design has become the focus of intense research efforts. This research has identified the conceptual stage of design as critical for both functional and innovative design. Of central importance at this stage is the interplay between two types of knowledge: abstract, conceptual knowledge and perceptually-based knowledge. Visuospatial reasoning is the cognitive process that links these two types of knowledge. This aspect of the design process forms the focus of this conference series.

We know that design entails visuospatial imagining, sketching and reasoning, but we are only now learning in detail how this happens. It is this knowledge that will provide insights to promote creative design through productive interaction with sketches. At its core, design is a cognitive process. Both designers and cognitive scientists have special but different insights into the design process. This conference brings together these two communities, those who have been studying the design process with those who have been studying visuospatial thinking with the goal of finding ways to facilitate design. The results of this conference are likely to have implications for the facilitation of visuospatial reasoning in other contexts as well: in constructing and understanding maps, diagrams, graphs, interfaces, and art as well as the many other visual messages that are ubiquitous today.

This, the proceedings of the Second International Conference on Visual and Spatial Reasoning in Design, contains 20 papers that span the range of research from the psychological to the computational. More than twice that number of papers was submitted; each paper was reviewed by three referees. The authors come from 9 different countries attesting to the spread of interest in this burgeoning field.

The support of the Key Centre of Design Computing and Cognition of the University of Sydney, the Rockefeller Foundation, and the Bellagio Conference Center in organizing this conference is gratefully acknowledged as is the assistance of the Office of Naval Research International Field Office. Anne Christian worked tirelessly to unify the multifarious interpretations of what were thought to be clear formatting instructions to produce a coherent volume.

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John Gero, Barbara Tversky and Terry Purcell
Sydney and Stanford
May 2001

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Bellagio Conference Center, Bellagio, Italy
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edited by
John S Gero
Barbara Tversky
Terry Purcell

2nd International Conference on Visual and Spatial Reasoning in Design
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