Visual Reasoning as a critical attribute in design creativity

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Abstract: A visual reasoning ability is a fundamental attribute in a creative design process. This research investigates how the visual reasoning ability is measured and explained through experiment and visual reasoning model. The experiments consist of four visual reasoning tasks such as missing view problem, constructive perception task, plan-perspective view matching task, and emergent shape task. We could observe different performances between experiment participants with different design experiences, and meaningful correlation between tasks. These results suggest that our devised visual reasoning task is valid and that visual reasoning ability is potentially related to design creativity. We explain visual reasoning abilities found from the tasks through visual reasoning model.

Keywords: Visual Reasoning, Design Creativity, Missing View Problem, Perspective Plan View Matching Task, Emergent Shape Task

1. INTRODUCTION

It is important to establish a concrete concept of design creativity and to find a distinct cognitive process for design problem solving in education of design creativity. At the Creative Design and Intelligent Tutoring Systems (CREDITS) research center, research work toward design creativity education is being conducted such that various underlying cognitive elements of design creativity are identified and then these design creativity elements can be enhanced through training methods reflecting individual learner's cognitive personal characteristics (Kim & Kang, 2003). As a critical element of design creativity, visual reasoning capability has been identified (Kim et al., 2005), and an intelligent tutoring system has been developed for visual reasoning (Wang & Kim, 2005). In this paper we assume visual reasoning can be measurable through diverse experimental tasks and analyzed statistically. Under these assumptions, we devised tasks to measure the visual reasoning ability of architecture students. In addition, we laid the foundation of visual reasoning model to explain the process of visual reasoning.

2. VISUAL REASONING AND DESIGN CREATIVITY

2.1 What is Visual Reasoning?

Basically reasoning can be defined as going beyond the information given (Bruner, 1973). In this aspect, Tversky (2005) suggested that there are two ways in going beyond the information: one is to transform information according rules and the other is to make inferences or judgments from the information. In visual reasoning the given information can be regarded as visual information such as designer's sketch. To transform or infer about such information, observation and interpretation of visual information should be preceded. Also, retrieval of rules and usage of visual knowledge are necessary. At last, externalization is needed for confirmation of the results. These processes can be explained in iterative process of seeing, imagining, and drawing: imagining process to synthesize in mind, the drawing process to represent the synthesis results, and the seeing process to analyze the drawings (McKim 1972). The nature of design reasoning as the iterative process of seeing-moving-seeing has also been discussed in Schon & Wiggins (1992). This could be viewed as analysis, synthesis, and evaluation. With the above intent, we define visual reasoning as an iterative process composed of visual analysis, visual synthesis and modeling so that these three would account for seeing, imagining and drawing, respectively.

2.2 Is Visual Reasoning Related to Design Creativity?

A number of researchers have found an interactive relation between visual reasoning and creative design (McFadzean & Cross, 1999; Tang, 2003; Soufi & Edmonds, 1996; Oxman, 1997). There have been trials to prove complex interaction between external representation and cognition through protocol analysis using video and computer records of designers' sketching activity (McFadzean & Cross, 1999). Through protocol analysis, Tang (2003) also verified that 'conceptual design process using sketches is a visual reasoning where sketch are the media amongst perceptual and conceptual knowledge, enabling the design process to happen.' In addition, Soufi & Edmonds (1996) supported emergent shape as a result of visual reasoning plays a significant role in the creative design process and they made an effort to develop the computational models capable of representing emergent shapes. Through an empirical study of designers' behavior in the graphical adaptation of a design solution, Oxman (1997) suggested that visual reasoning is critical role in design creativity. From preceding studies we can convince visual reasoning is essentially related to design creativity.

2.3 What Kinds of Tasks Can Be Devised as A Visual Reasoning Test?

There have been different trials to reveal the visual reasoning abilities in experimental studies (Liu, 1995; Suwa & Tversky, 2003; Kim et al., 2005). Liu (1995) devised experimental task to discover sub-shapes. In his study experts found more implicit sub-shapes than novices. This result means that visual reasoning task can prove different ability between expert and novices. Also, Suwa & Tversky (2003) proved that their *constructive perception (CP) task* was valuable in comparing visual reasoning ability between experts and novices. In CP task they found that expert designers generated more interpretations about ambiguous pictures than novice designers. In addition, Kim et al (2005) proved that in visual reasoning ability task, so-called *missing view problem (MV) task*, there were different performances between engineering, industrial design, and psychology students. Industrial design students who were assumed to be most creative among groups obtained the highest scores in MV task. Besides, scores of MV task was correlated with design creativity scores of students. Accordingly, visual reasoning ability can be measurable through experimental tasks. If we devise visual reasoning tasks more to find diverse underlying aspects of visual reasoning ability, we can understand better how visual reasoning contributes to design creativity. In this paper we will introduce new visual reasoning tasks. One is *perspective-plan view matching (PPM) task* which enables us to measure ability in extraction of predicate in architectural space, imagery simulation, and visual working memory. Another is *emergent shape (ES) task* which make it possible to test an ability to interpret visual information and infer unexpected shapes.

3. EXPERIMENT

14 first grade and 23 second grade architecture students conducted four kinds of visual reasoning task such as MV task (Kim et al., 2005), CP task (Suwa & Tversky, 2003), PPM task, and ES task to measure a visual reasoning ability. Our hypothesis was our devised visual reasoning task would be proper to measure visual reasoning ability. Therefore, we expected that second grade students would perform better in all visual reasoning tasks than first grade students if the tasks measure visual reasoning ability properly. It is because that over 1 year educated students (second grade students) could be assumed to have more visual reasoning ability than non-educated students (first grade students). In addition, it is expected that the visual reasoning tasks would be correlated with each other if the tasks measure same visual reasoning abilities.

MV task. In MV task, according to Kim et al. (2005)'s method, much explanation on how to solve the problems is not provided, but a very general introduction on perspective projection and orthographic projections. Participants are required to construct a valid 3-D solid object visually by analyzing two 2-D orthographic projections and to form the missing view orthographic projection. They should find solution satisfying these geometric constraints given with two orthographic views (Figure 1).

CP task. In CP task, participants are asked to generate as many as possible interpretations about four kinds of ambiguous pictures and to write down their interpretation (Figure 2).

PPM task. In PPM task, a plan view of an architectural structure is given, and then pictures of multiple structures similar to the plan view are given with a picture of the very correct architecture (Figure 3). With three iterations of these for 15 seconds each, a correct architecture is to be selected (Figure 4).

ES task. In ES task architectural sketches is given, and then meaningful shapes which construct architectural sketches is to be inferred and drawn. Therefore, participants should reason which kinds of shapes the architecture designer overlapped to design an architectural sketch and draw the inferred shapes (Figure 5).

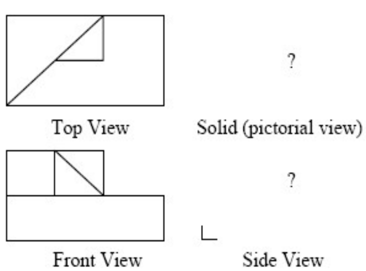

Figure 1 Missing view problem as an example

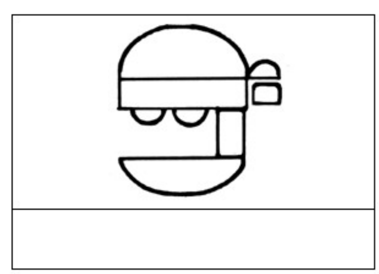

Figure 2 Constructive perception task as an example

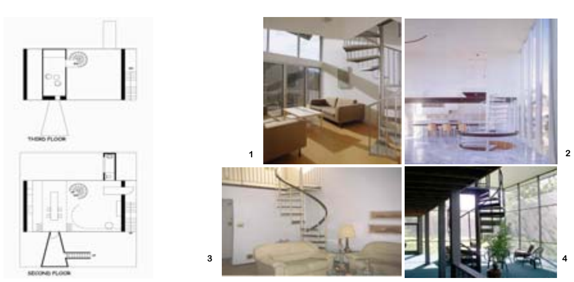

Figure 3 Example problem and multiple choices of PPM task

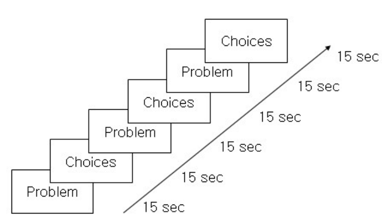

Figure 4 Procedure of PPM task

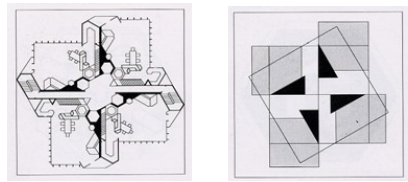

Figure 5 Example problem and answer of ES task

4 RESULTS AND DISCUSSION

In MV task, two evaluators assessed the answers of MV task. They reduced by 3 or 5 points whenever the answer was incorrect in some part. In CP task, we counted the number of different interpretations and sum all of them from four kinds of pictures. We did not evaluate the value of ideas just as Suwa and Tversky did (Suwa & Tversky, 2003). In PPM task, we recorded correctness and evaluated the participants' answers about why the participants chose the answer. In case where the answer was not enough to explain their choice, we reduced by 3 points even though their choice was right. In ES task, four evaluators who had more 10 years experiences in architecture design assessed the answers of emergent shape. Scores from four evaluators had significant correlations each other; therefore, we used average scores of four evaluators. This also means ES scores are confident and ES task is reliable to test. Table 1 shows correlations between 4 evaluators.

4.1 Difference between First and Second Grade Architecture Students

A repeated measure ANOVA was carried on the scores of each task. Figure 6 summarizes the results. We observed difference between first and second grade architecture students in visual reasoning tasks, $F(1, 35) = 12.398$, $p<.01$. An interaction effect between tasks and groups was not obtained, $F(3, 33) = 1.339$, $p>.05$. That means second grade students had higher scores than first grade in all visual tasks consistently. This result was consistent with our expectation. Considering that second grade students has been educated for over one year in architecture and first

Table 1 Correlation of ES scores between four evaluators.

	Evaluator 1	Evaluator 2	Evaluator 3	Evaluator 4
Evaluator 1	1	.120	.542**	.471**
Evaluator 2		1	.478**	.548**
Evaluator 3			1	.688**
Evaluator 4				1

** Correlation is significant at the 0.01 level.

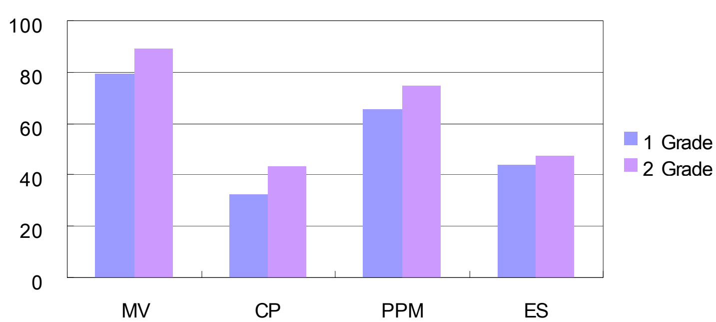

Figure 6 Mean scores of first and second architecture students in each task

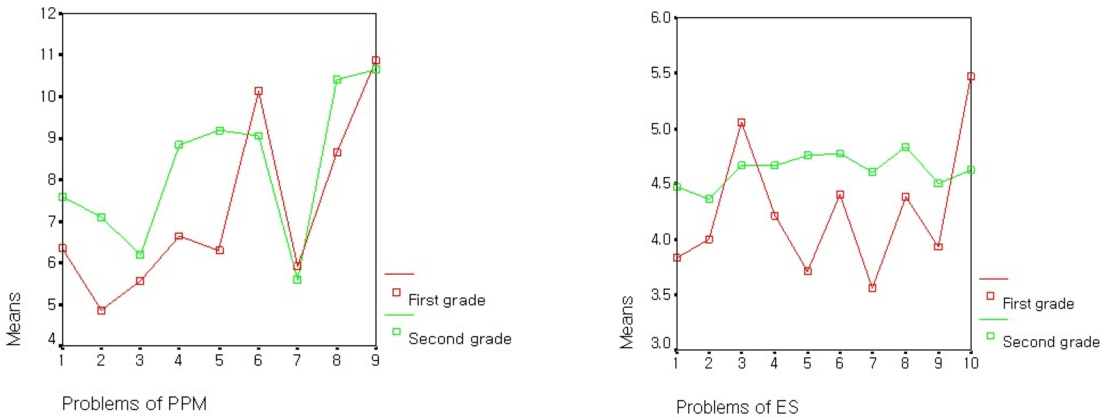

Figure 7 Mean scores of first and second grade students in each problem of PPM and ES task

grade students have almost not, this different performance means these tasks reflect a degree of education. From knowing that architectural education includes improving design ability such as idea generation training and imaging space from architectural plan view, this result suggests these tasks have values as a measure tool of architectural design ability.

In addition, we analyzed each mean score from problems of our new devised PPM and ES tasks. As a result, different pattern was found between first and second grade students in each task. As Figure 7 shows, performances of second grade students were generally higher than first grade students. In addition, consistent pattern of ES task is found in second grade students. This means second grade students' visual reasoning ability reveals in ES task consistently. It might be because second grade students' visual reasoning ability is more developed stably. In case of PPM task, the performance of each problem is unstable in both first and second grade students so that we need to consider levels and arrangements of PPM problems. In the future study we will adjust PPM problems for more stable measurement.

4.2 Correlations

We analyzed correlations between scores of tasks in sum of first and second architecture students' scores. It is meaningful that MV task and other tasks such as PPM and ES task had significant correlation (Table 2). Since MV task has been acknowledged as a representative visual reasoning task (Kim et al., 2001; Kim et al., 2005), PPM and ES task also can be convinced to require visual reasoning ability. Furthermore, MV task was proved to be related to design creativity in Kim et al. (2005); therefore, we can interpret that PPM and ES task is potentially related to design creativity from our results. MV, PPM, and ES tasks seem to require common visual reasoning ability related

Table 2 Correlation of MV, CP, PPM, and ES task

	MV	CP	PPM	ES
MV	1	.067	.409**	.365*
CP		1	.029	.189
PPM			1	.071
ES				1
Design				

** Correlation is significant at the 0.01 level.
* Correlation is significant at the 0.05 level.

to design creativity. In addition, PPM and ES task were not correlated with each other while MV task was correlated with PPM and ES task. From this result, we interpreted that PPM and ES task have little common visual reasoning abilities whereas MV task includes more common visual reasoning abilities with both PPM and ES task. In next section we analyzed the each task; as a result, we could find different abilities were required in PPM and ES task.

Unfortunately, CP task was not correlated with any other tasks. It was same result as Kim et al. (2005). In their study the different performances between industrial design, engineering, and psychological students was also obtained, but there were no correlation between CP and other tasks such as MV and design task. Because Suwa & Tversky (2003) found CP scores of experts were higher than novices, it could be expected that CP task is related to design creativity. However, CP task was not directly related to design creativity (Kim et al., 2005) rather it was related to specialty or design education. Especially CP task seems to be more related to associative fluency: Suwa & Tversky (2003) proved that CP task is related to associative fluency which is defined as the ability to produce words in a restricted area of meaning. Therefore, we excluded CP task in further explanation of visual reasoning and design creativity.

5. VISUAL REASONING MODEL

We scrutinize visual reasoning abilities required in visual reasoning task. At first, visual reasoning process is discussed and visual reasoning model is presented. Then, we look into specific visual reasoning abilities in each task.

5.1 Visual Reasoning Process

Visual reasoning process includes visual analysis, synthesis, and modeling process which can be viewed as seeing, imagining, and drawing process (McKim, 1972) as we defined visual reasoning. These processes occur in the interaction with perceptual and conceptual process.

Seeing. In seeing process, visual *perception (P), analysis (A),* and *interpretation (I)* occur. In *perception*, identification of primitives, combination of primitives, and recognition about the visual information occur. In *analysis*, observation about relations of primitives and exploration about predicates of the visual information occur. In *interpretation*, naming, categorization, and giving new meaning to the perceived objects occur with memory. This process brings about extraction of predicates as needed for new image generation and transformation.

Imagining. Imagining process enables to synthesize using conceptual and conceptual information for new representation. Imagining process can be classified as *generation (G), transformation (T),* and *maintenance (M).* These three components were mentioned by Kosslyn (1995), together with the fourth component of inspection to account for imagery process. In earlier Kavakli & Gero (2002)'s work, generation and transformation were proved to be critical in creative design process. Image *generation* occurs with two ways: one is from perceptual input online through seeing process and the other one is from activated knowledge and schema stored in long term memory (LTM) (Kosslyn, 1995). Image *transformation* can be differentiated with two kinds: congruent transformation and pattern change transformation. Kosslyn (1995) defined image transformation as limited meaning similar with physical perception such as mental rotation and image size change. We categorized this kind of transformation as congruent transformation. On the other hand, Oxman (2002) suggested 'image pattern altering' process such as emergent shape. We categorized this kind of transformation as pattern change transformation. After the image transformation, image *maintenance* occurs for keeping the internal representation.

Drawing. Drawing process enables representation through both ways to internalize and to externalize. In *internal* *representation (IR)*, the transformed image is to be confirmed. This process occurs in the interaction with imagining and seeing process. In addition, e*xternal representation (ER)* serves as external memory, in which to leave ideas as visual tokens, so that they may be revisited later for inspection (Suwa, Purcell, & Gero, 1998). In the process of conversion from internal representation to external representation, generation of imagining process can occur as well. That is why drawing process is important in visual reasoning. Also, the drawing process enables to manipulate and transform the images. In this way sketch can facilitate visual reasoning.

Knowledge & Schema. *Knowledge (K)* and *schema (S)* are engaged in the interaction with visual reasoning process. Schon (1983) suggested that empirical knowledge such as test information and image information affects the iterative process of framing, moving, and reflection. That is, retrieval of visual knowledge from LTM becomes a cue to match between visual input and visual memory for visual perception in seeing process. Also, by visual schema retrieved from LTM which becomes a rule for extraction of predicate, visual information can be reorganized in iteration process of seeing and imagining. These iterative processes make it possible to transform and modify the existing visual input in imagining process. Oxman (2002) also suggested that it is important to know how to transform and the ability to access schema of basic structure is essential in reformulating images. In addition, order and pattern of drawing can cause different visual reasoning according to designer’s drawing schema. The schema can play a critical role to link between conceptual and perceptual process in drawing process. As a result, diverse manipulation of images can be generated.

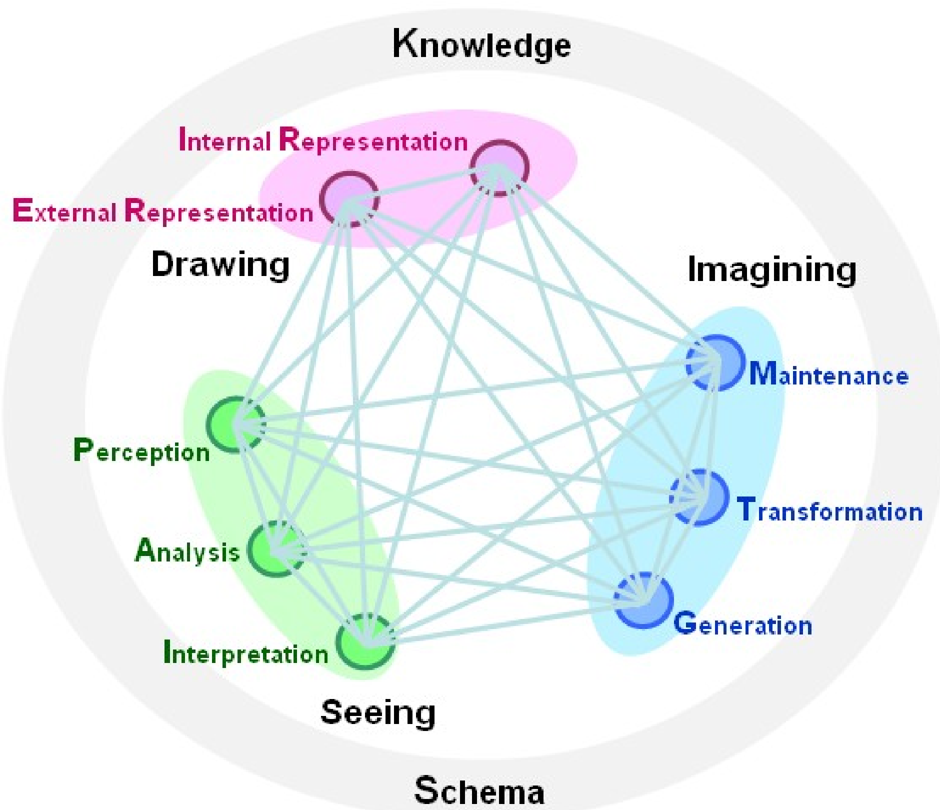

Figure 8 The visual reasoning model

As we looked into visual reasoning process, seeing, imagining, and drawing process occur not independently but interactively with knowledge and schema: in all visual reasoning process, there exists interaction between perceptual and conceptual knowledge. Oxman (2002) emphasized that perception and conception process can provide a working basis for conceptualizing visual cognition in design. Arnheim (1960) also mentioned that a dependent relationship between perception and visual cognition: 'only because perception gathers types of things, that is concepts, can perceptual material be used for thought'. Therefore, visual reasoning is linking process between perceptual and conceptual knowledge (Tversky, 1999). This is our visual reasoning process model and it is illustrated in Figure 8.

5.2 Visual Reasoning Abilities Derived from Each Task

MV task. MV task requires extracting of predicates from problem for searching linking part of projections from different two views through visual perception (P) and analysis (A). Then, alternative images can be generated (G) with visual knowledge (K) such as experience of projections. If the participant have affluent experience of projections and schema know how to transfer (S), it is easy to construct and transform images. In internal representation (IR), generated images can be inspected comparing with given sketches (P & A). Also, through sketching, image externalization occurs (ER), and the image can be transformed (T) continuously by repetitive analysis about sketches (A). To form the solutions, MV task also requires transforming structure from 2D to 3D or from 3D to 2D (T). At the same time, visual perception (P) occurs comparing with given sketches and potential results. In this process, congruent transformation (T) can occur to reach the solution.

PPM task. PPM task requires interpreting the problem representation (I) through visual perception (P) and analysis (A); as a result, extraction of predicates to remember from the problem for comparing with choices effectively occurs. Then, the generated images (G) should be maintained (M) for searching answers because the choices are presented after the problem disappearing on the screen. According to kinds of problems, it is differently acquired to convert plan view into space view or space view into plan view, transformation (T) is necessary in imagining process. In internal representation (IR), the image should be inspected for comparison with perceived multiple choices (P & A). Also, about multiple choices, visual interpretation about spaces and extraction of predicates for comparing with generated image occur. In case where the problem and the choices are not same direction, congruent transformation should be required (T). Surely, the domain specific knowledge (K) about architectural plan view is important for solving this task.

ES task. ES task requires interpretation about shapes (I) through visual perception (P) and analysis (A); as a result, extraction of predicates to transform occurs. Now that participant should infer how the architecture designers constructed the architectural design, image transformation (T) such as deconstruction and reorganization of original sketches are required in imagining process. In this inference process visual knowledge about shapes can be associated. When the process is made in mind (IR), image inspection and transformation can occur repetitively. In addition, drawing process to represent the image explicitly (ER) is important because in this process the image can be also transformed (T) from mental images with interactive shape schema (S). Then, visual perception (P) occurs for comparing with given sketches and potential results.

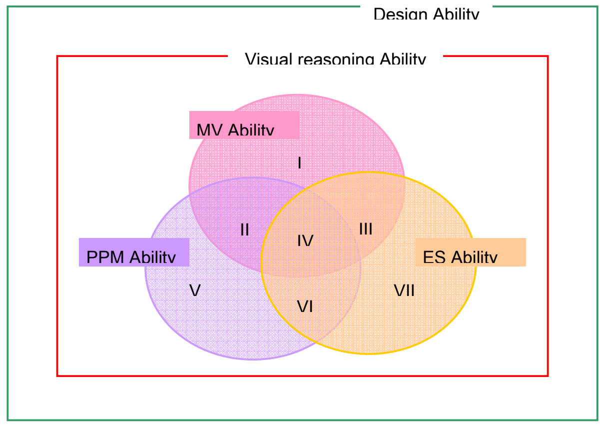

Figure 9 Diagram of visual reasoning ability from each task in design process

5.3 Relation to Correlation Results from Our Experiment

Visual reasoning abilities from task analysis were found in this paper. These visual reasoning abilities can be roughly classified such as Figure 9. From this analysis, we can conjecture why correlations between visual reasoning tasks were different in our experiment. Although common visual reasoning abilities are required in all visual reasoning tasks, there are some kinds of visual reasoning abilities differently required according to the characteristic of visual reasoning task. For example, visual knowledge about underlying structure or orthographic and how to construct projections are possibly required in MV task (I). Interpretation of architectural plan views and image maintenance ability are mainly required in PPM task (V). Also, in ES task, visual knowledge about shape is inevitably required (VII). 2D, 3D, and congruent transformation abilities are mainly required in MV and PPM task (II) while pattern change transformation ability is mainly required in ES task (VII). In addition, externalization of representation is not required in PPM task but in MV and ES task (III). Accordingly, MV task measures more various abilities than PPM and ES task. Also, we can know that PPM and ES task have little common aspects. Probably, that is the reason why MV was correlated with PPM and ES task, but PPM and ES was not correlated with each other.

5.4 Relation to Other Researches

From analysis of visual reasoning task, we could find several visual reasoning abilities which were proved to be important in design process. First, visual knowledge about underlying structure or schema has been acknowledged to be significant in design process in Oxman's study (2002). Also, 2D to 3D ability required both in MV and PPM task has been assumed to core design ability (Ho, Eastman, & Catrambone, 2006) and studied how two types of representations interact (Goldshmidt, 1991; Larkin & Simon, 1987). In addition, interpretation about sketches required in ES task has been acknowledged to be important in advancing design process because it enables to retrieve knowledge and provoke unexpected discovery (Tang, 2003). McFadzean & Cross (1999) also proved visual reasoning in design is facilitated by sketching through computational sketch analysis. Even though mental rotation such as congruent transformation is required in MV and PPM task, this ability seem not to be related to design creativity. Mental rotation has been acknowledged as general spatial ability (Linn & Petersen, 1986), and MV task was proved to be correlated with spatial task (Kim et al., 2005). However, spatial ability of MV task might not be related to design creativity directly now that spatial task was not correlated with design creativity (Kim et al., 2005; Suwa & Tversky, 2003).

6. CONCLUSION

Visual reasoning has been acknowledged as a fundamental attribute in a creative design process. Visual reasoning can be defined as an iterative process composed of visual analysis, visual synthesis and modeling and these three make design more creative. We devised new visual reasoning task which reflect these processes for investigating visual reasoning attributes more specifically. From our results that second grade students had better performances than first grade students in visual reasoning tasks and MV task had correlation with PPM and ES task, our devised visual reasoning tasks are reliable to test and related to design creativity potentially. Therefore, we analyzed visual reasoning abilities from visual reasoning tasks and explained in visual reasoning model. We classified three processes into eight components in visual reasoning model in which seeing, imagining, and drawing process iteratively proceed, and each component is interacted with visual knowledge and schema. Through this model, we tried to explain how the visual reasoning components are working in each visual reasoning task so that we could find characteristics of each task and components required from the task. In the future study we will continue to find what visual reasoning is and how it is related to design creativity more and further through various visual reasoning tasks and analysis of these tasks. Therefore, we have a plan to devise more visual reasoning task which can measure other aspects of design creativity and to analyze these tasks through protocol analysis.

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