The Impact of Visualization Tendency
in Phases of Problem-solving

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Problem-solving ability is one of the most important learning outcomes for students to compete and accomplish in a knowledge-based society. It has been empirically proven that visualization plays a central role in problem-solving. The best performing problem-solver might have a strong visualization tendency. However, there is little research as to what factors of visualization tendency primarily related to problem-solving ability according to phases of problem-solving. The purpose of this study is to identify the relationship between visualization tendency and problem-solving ability, to determine which factors of visualization tendency influence problem-solving ability in each phase of problem-solving, and to examine different problem-solving ability from the perspective of the levels of visualization tendency. This study has found out that visualization tendency has a significant correlation with problem-solving ability. Especially, Generative Visualization and Spatial–Motor Visualization as sub-visualization tendency were more strongly related to each phase of problem-solving. It indicates that visualization tendency to generate and operate mental processing can be considered a major cognitive skill to improve problem-solving ability. Furthermore, students who have high visualization tendency also have significantly higher problem-solving ability than students with low visualization tendency. It shows that the levels of visualization tendency can predict variables related to students' problem-solving ability..[1]

Keywords: *Visualization tendency, Internal cognitive processing, Internal representation, Problem-solving*

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Introduction

Problem-solving is one of the most important learning outcomes in the educational context (Davis & Linn, 2000; Jonassen, 2000; Lasley, Matczyncki, & Rowley, 2002; Reigeluth & Joseph, 2002). In everyday life, facing challenges in education, work, and business, people encounter a lot of problems. To solve those problems, they need to use the knowledge and skills they have learned in school and elsewhere by applying critical and creative thinking to unfamiliar situations (OECD, 2004). That is, problem-solving ability has a prominent role in helping us compete and accomplish in the knowledge-based society of the 21st century.

Problem-solving is a complex cognitive processing which is inductive and deductive reasoning including visual/spatial thinking. According to Mayer (1994), a good problem-solver tends to connect all kinds of cognitive processing. He reported that if a problem-solver builds useful visual representations and connects them with relevant inductive and deductive reasoning processes in a problem-solving context, he or she might be able to solve the problem immediately and creatively. In short, cognitive processing based on visualization may be one of the most important roles for problem-solving (Cuevas, Fiore, & Oser, 2002; Glaser & Chi, 1988; Keller & Tergan, 2005; Klein, 1989; Kozhevnikov, Motes, & Hegarty, 2007; Quintana, Krajicik, & Soloway, 2001). Visualization refers to cognitive or mental processing that visually transforms perceived stimuli into internal mental representations by generating, manipulating, and interpreting them.

In problem-solving, the power of visualization comes from the fact that it is possible to represent a problem visually by means of internal mental processing; the problem-solver can understand and identify easily how the elements in the problem relate to each other (Keller & Tergan, 2005; Ware, 2004). Visualizations can make use of the automatic cognitive process of pattern-finding (Ware, 2004) as well as can enhance our processing ability by visualizing abstract relationships between visualized elements, and may serve as a basis for externalized cognition (Cox, 1999;

Scaife & Rogers, 1996). Visualization facilitates the problem-solver's easier understanding of problems, which means that they require relatively a smaller cognitive load (Jonassen & Hung, 2006; Schwartz & Heiser, 2006; Sweller & Chandler, 1994). Visualization helps the problem-solver achieve better recall and retention of elements or clues of problems (Carroll, 1993; Lohr, 2008). Additionally, visualization facilitates reasoning ability during the process of problem-solving by using verbal and visual processing codes interchangeably (Baddeley, 1998; Cox & Brna, 1995; Larkin & Simon, 1987; Larkin, 1989; Mayer, 1994).

Many empirical evidences show that visualization plays a central role in problem-solving. Nevertheless, there is a lack of concrete evidence about what kinds of visualization factors are related to problem-solving ability as well as in each phase of problem-solving. Based on this fundamental question, we have elicited three sub questions. First, does visualization affect in the same way all steps of problem-solving which are composed of five phases such as understanding the problem, devising a plan, carrying out the plan, and looking back? Second, what kinds of visualization factors such as generative visualization, spatial–motor visualization, instrumental visualization, proactive visualization, and representative visualization primarily affect problem-solving ability in each phase of problem-solving? Finally, are there differences between a high visualizer who has a strong visualization tendency to solve a problem and a low visualizer who has a weak visualization tendency?

To combat this problem, we attempted to explore previous findings on the visualization effect in problem-solving in pursuit of three goals. The first goal is to examine the relationships between visualization and phases of problem-solving such as understanding the problem, identifying the cause of the problem, devising a plan, carrying out the plan, and evaluating results. The second goal is to determine which visualization factors affect problem-solving ability as well as each of these five phases. The final goal is to examine differences in problem-solving ability according to level of visualization; a high-scoring group versus a low-scoring group.

We predicted that visualization would be correlated with problem-solving ability, and that different visualization factors would come into play in different steps of problem-solving process. Also, we expected that a problem-solver who has a strong tendency in visualization would have better problem-solving ability than one who has a weak tendency in visualization.

Literature Review

Visualization as an internal cognitive processing

Visualization is widely applied as a technique in the field of education. The reasons are as follows according to previous research. First, visualization helps the learner to process and deal effectively with complex knowledge and ill-structured problems (Holley & Dansereau, 1984; Jonassen, Reeves, Hong, Harvey, & Peters, 1997; Jonassen, 2000; Rha & Sung, 2007; Sung, 2011). Second, visualization may reduce cognitive load (Sweller & Chandler, 1994) and expand the capacity of an individual's memory to cope with complex task (Cox & Brna, 1995; Larkin & Simon, 1987; Larkin, 1989). Last, external representations visualizing the inherent structures of an individual's knowledge, which may involve a great amount of information, can help people engaged in searching and cognitive processing of structured elements (Potelle & Rouet, 2003; Wiegmann, Dansereau, McCagg, Rewey, & Pitre, 1992). In short, visualizations can enhance our cognitive processing by representing abstract reasoning relationships between visualized elements and serve as a basis for externalized cognition (Cox, 1999; Scaife & Rogers, 1996).

Those evidences are supported by dual coding theory as summarized in Figure 1. The theory proposes two types of information processing system (Paivio, 1986): (a) a verbal or linguistic-information processing system called 'logogens' that operates sequentially—words come one at a time in a syntactically appropriate sequence

such as a sentence; and (b) a visual or imagery-information processing system called 'imagens' that operates synchronously or in parallel, so that all parts of an image are available for processing at once. The theory also proposes that three types of connections can be constructed by learners when they are presented with verbal and visual stimuli (Mayer, 1994): (a) representational connections between verbally presented information and a verbal representation, (b) representational connections between visually presented information and a visual representation, and (c) referential connections between elements in the verbal and visual representations.
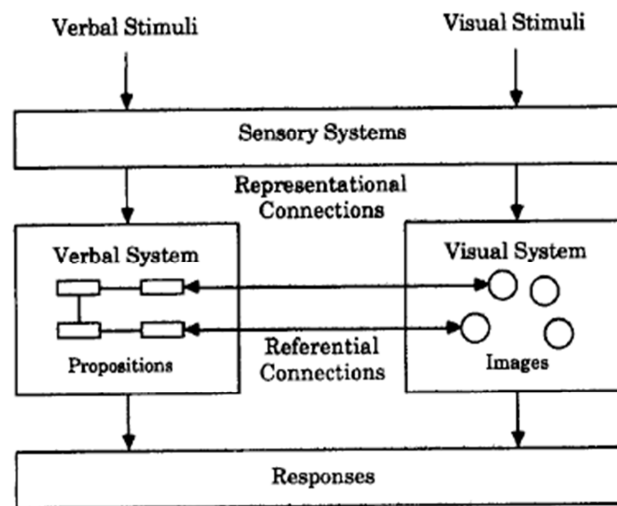
Figure 1. Dual-Coding Model of Learning from Words and Pictures (Mayer & Anderson, 1991)

However, these definitions remain general, and no one definition of visualization has been specified to multiple contexts. Actually, the term 'visualization' is often integrated into narrower or broader terms such as spatial visualization, spatial ability, visual ability, or visual thinking (Braukmann & Pedras, 1993). The term 'visualization' is considered to include both internal and external representations (Corter & Zahner, 2007; Rieber, 1995). In general, internal representation is a kind of synonym for the mental imagery that is created and manipulated as a mental

object or a process by externalization. External representation refers to the construction of pictures, graphics, or forms by internalization. In mathematics education, 'visualization' has been used as synonymous to spatial visualization (Bishop, 1989), which is considered a sub-concept of spatial ability (Battista, 1990; Casey, 2003; Halpern, 2000; Presmeg, 1986). McKim (1980) defined visual thinking as broader than visualization, because visual thinking is related to recognizing and manipulating all types of symbols both physically and mentally. In short, most visualization-related terms have broad definitions that mainly concentrate on the mental interaction between internal and/or external representations with a focus on classroom or academic settings. That is, the research on visualization of human beings has been confined to what occurs in classroom. Therefore, more research needs to be done on visualization as one omnipresent characteristic which human beings have regardless of when and what they do.

Visualization tendency as a degree of visual thinking

Recently, more specified definition of visualization has been proposed by researchers (Rha, Sung, & Park, 2010; Sung, 2011; Sung, Leem, & Kim, 2010). They defined Visualization Tendency (VT) as a degree of a mental processing ability for visually transforming, generating, manipulating, operating, recreating, or representing information in a meaningful way for everyday life where problem-solving skills are needed. They proposed that visualization tendency as a degree of visual thinking comprises of five factors: Generative Visualization (GV), Spatial–Motor Visualization (SV), Instrumental Visualization (VI), Proactive Visualization (PV), and Representative Visualization (RV). GV refers to cognitive reasoning activity that associates similar things or infers their mechanisms by seeing them (e.g., we tend to associate things with others that look similar; and we tend to infer related or influencing factors when we see things). SV refers to mentally manipulating or operating two- or three-dimensional figures (e.g., we can easily

guess where a ball will land when we throw it; we tend to picture the imagined arrangement of furniture while moving it about in a room). IV refers to instrumental representation in easy-to-understand visual formats such as images, graphs, tables, diagrams, charts, graphic organizers, and so forth (e.g., we tend to draw diagrams or pictures when we attempt to figure out complicated matters). PV refers to imagining or fantasizing mental images of the future or counterfactual situations (e.g., we usually imagine our future with clear pictures or images). Finally, RV refers to the reproduction of a single non-visual sense modality to a visual format (e.g., we usually think of scenes or images related to the melodies or lyrics while listening to music). In this study, as mentioned above, visualization tendency is a degree of visual thinking that is considered to include all possible human actions whereby visualization activities can be internalized and/or externalized in everyday life situations.

The central role of visualization in problem-solving

Visualization is one of the most important factors affecting problem-solving (Cuevas, Fiore, & Oser, 2002; Glaser & Chi, 1988; Keller & Tergan, 2005; Klein, 1989; Quintana, Krajicik, & Soloway, 2001). The use of visualization or visual aids is more likely to reduce students' cognitive load, especially during problem-solving (Sweller & Chandler, 1994). Studies have considered visualization crucial for problem-solving processes (Finke, 1990; Finke, Ward, & Smith, 1992). Bransford and Stein (1993) put an emphasis on visualization because the transformation of a problem into visual form makes it easy to derive a solution. It is also argued that most visualization skills and abilities can be developed through use (Tuckey & Selvaratnam, 1993; Stokes, 2002).

The literature has mentioned a high correlation between visualization activities and problem-solving ability (McGee, 1979). The implementation of visualization activities as part of task instructions has helped students achieve balanced learning

by using both their left and right brains (Williams, 1983). Visualization activities improve students' intuitive, creative, and integrated thinking (Root-Bernstein & Root-Bernstein, 1999). In addition, visual scaffolding supported by diagrams and mind maps has been shown to improve students' understanding of the structure of learning contents leading to increased learning achievement (Cuevas, Fiore, & Oser, 2002; Quintana, Krajicik, & Soloway, 2001; Rha & Park, 2010). The relationship between visualization and problem-solving can be summarized as follows. First, visualization helps students to comprehend problem situations, their components, and the relevant details for problem-solving (Holley & Dansereau, 1984; Jonassen, Reeves, Hong, Harvey, & Peters, 1997; Keller & Tergan, 2005; Nathan, Kintsch, & Young, 1992). Visualization facilitates understanding of problems with a smaller cognitive load needed (Jonassen & Hung, 2006; Schwartz & Heiser, 2006). Visualization allows formation of mental models of problems as well as goals for problem-solving. For example, flowcharts, concept-maps, and diagrams are effective tools for solving complicated problems. Second, visualization helps students to have better recall and retention of problem elements during problem-solving processes (Carroll, 1993; Corter & Zahner, 2007; Hodes, 1992; Keller & Tergan, 2005; Lohr, 2008). Visualization helps students to represent problem-solving processes and contexts in visual format. It is thought that visualization imposes its own visual forms upon the information for problem-solving, which allows students to better memorize and understand it. Finally, visualization facilitates reasoning ability for problem-solving (Corter & Zahner, 2007; Scheiter, Gerjets, & Catrambone, 2004; Sedlmeier, 2000). Visual representation for problem-solving stimulates students' reasoning skills or ability in problem-solving processes (Jonassen & Hung, 2006), and visual scaffolding strategies elicit students' thinking processes in the problem-solving context, which leads to increased learning achievement (Rha & Park, 2010).

High performers in problem-solving are more likely to recognize the nature of a problem and visualize an effective mental model of a solution (Glaser & Chi, 1988;

Keller & Tergan, 2005; Klein, 1989; Woodland & Szul, 1999). Thus, it can be expected that a specific visualization will play an important role in a specific problem-solving process. However, not many studies have considered how problem-solving processes are related to specific visualization factors.

In terms of the relationship between visualization and problem-solving processes, a variety of general problem-solving processes have been suggested (Ernst & Newell, 1969; Kruik & Rundnik, 1987; Schoenfeld, 1980). Jang (2005) derived four comprehensive processes from previous studies: understanding the problem, devising a solution, implementing the solution, and revising. However, Park (1997) argued that it was necessary to teach specific processes and strategies to be used for each of the problem-solving phases. Additionally, it is said that knowing principles and procedures on top of specific content knowledge for problem-solving plays an important role when students solve problems (Gagne, 1985). Regardless of the subject matter or the situational knowledge needed, problem-solving strategies should be usable for the problem-solving process (Polya, 1957).

Even though different kinds of visuals and various problem-solving strategies are used for problem-solving processes, it is not easy to determine what visualization factors are related to problem-solving processes. Recently, one study conducted on 239 fifth-grade students discovered that Generative Visualization ability strongly predicted problem-solving ability, while Representative Visualization was the least significant factor. Throughout the whole problem-solving processes, Generative Visualization was the most (positively) influential factor on every process of problem-solving (Rha, Sung, & Park, 2010). However, it is in the planning and implementing process that Spatial–Motor Visualization affects the process most significantly.

Method

Participants

One hundred and one participants were recruited from the Education subject pool at a major university in South Korea. The average age of the participants was 21.01 years old (SD=1.76) years, and the mean for university year was 2.38 (SD=0.95) years. There were 75 women and 26 men that there was no significant on gender differences on scores of visualization tendency, t=.825, p=.411, however, there was significant differences on gender on problem solving ability that male students are higher than female students, t=2.400, p=.018. All participants had successfully completed more than four semesters and achieved over 3.00 on a 4.5 GPA (on average, a 3.73 GPA).

Instrument

The paper-based materials comprised a participant questionnaire, a visualization tendency questionnaire (VTQ), and a problem-solving ability questionnaire (PSQ). The participant questionnaire solicited demographic information concerning participants' age, gender, school year, and GPA. The VTQ comprised 20 items assessing visualization tendency toward cognitive transformation from various information modalities into visual formats on a five-point Likert rating scale (with 1="very little," 5="very much"), as shown in Table 1 (Rha, Park, Choi, & Choi, 2009). VTQ items clustered into five factors; Generative Visualization (GV), Spatial–Motor Visualization (SV), Instrumental Visualization (VI), Proactive Visualization (PV), and Representative Visualization (RV). The reliability coefficient obtained by Cronbach's alpha for the entire VTQ was 0.85, which shows suitable reliability. The five factors' individual reliability coefficients as indicated in parentheses were GV (0.76), SV (0.72), IV (0.74), PV (0.70), and RV (0.75).

The instrument for measuring problem-solving ability was modified from Ryu et al. (2004). It consisted of 45 items assessing problem-solving ability in adults on a five-point Likert rating scale (with 1="very little," 5="very much") (Ryu, Kim, Lee, & Song, 2004). PSQ clustered into five categories including understanding the problem (UP; e.g., first of all, the respondent identifies the problem he or she has to solve); identifying the cause of the problem (IP; e.g., collecting information about similar problems to determine what is cause and what is effect); devising a plan (DP; e.g., positively accepting others' ideas even if the respondent disagrees); carrying out the plan (CP; e.g., classifying the problem's components to determine what should be done first or later); and evaluating results (ER; e.g., asking for other people's opinions about the solution suggested). PSQ was developed to measure the mental capacity of adults to solve problems. The reliability coefficient obtained by Cronbach's alpha for the entire questionnaire was 0.85, which was suitable. The five categories' individual reliability coefficients are indicated in parentheses: IP (0.81), AC (0.84), ES (0.81), PI (0.83), and ER (0.81).

Procedure

Participants responded to three types of paper-based questionnaires, as described above: a participant questionnaire, a visualization questionnaire, and a problem-solving ability questionnaire. First, the researchers briefly explained the purpose of the study, the procedure for the test, and some simple instructions to follow. Second, participants were asked to sign an informed-consent form. Third, they filled out the participant questionnaire. Fourth, they completed the 10-minute long VTQ. Fifth, participants responded to the 20-minute long PSQ. Finally, participants were asked if they had any questions, and the researchers thanked the participants. We have conducted this process two times because participants were divided two classes in University.

Data analysis

The purpose of this study was to identify the relationship between visualization tendency and problem-solving ability. To address this goal, data analysis was conducted in two phases. The first phase involved the use of correlation analysis and multiple regressions to identify predictor variables of visualization ability for problem-solving ability.

Regression analyses were conducted to test linearity and multi-collinearity, with the results (tolerance=0.58 ~ 0.81 (tolerance>0.1), VIF=1.23–1.73 (VIF<10)) indicating that the assumptions of the regression had certainly been met. In addition, according to the result of fitting the model of regression, it was highly significant (F(5, 95)=12.01, p<.01), indicating that the null hypothesis can be rejected.

The second phase of data analysis involved not only a t-test to identify significant differences between the two groups (strong and weak group) according to the visualization tendency, but also discriminant analysis to accurately identify significant differences between the two groups.

Results

Means and standard deviations of visualization tendency and problem-solving ability

The mean ratings and standard deviations of visualization tendency and problem-solving ability scores are presented in Table 1. As can be seen in the first column in the visualization section, the overall mean rating of visualization tendency was M=3.57, SD=0.51. Among the means of visualization tendency factors, Representation Visualization had the highest score (M=3.94, SD=0.75) and

Generative Visualization the lowest (M=3.34, SD=0.59). The overall mean rating of problem-solving ability was M=3.56, SD=0.40. Among the means of problem-solving factors, 'Understanding the Problem' received the highest score (M=3.81, SD=0.55) and 'Devising a Plan' the lowest (M=3.35, SD=0.51).

Table 1. Mean ratings and standard deviations of visualization ability and problem-solving ability (n = 101)

Visualization Tendency	M	SD	Problem-Solving	M	SD
Generative Visualization	3.34	0.77	Understanding the Problem	3.81	0.55
Spatial–Motor Visualization	3.43	0.59	Identifying the Cause of the Problem	3.63	0.44
Instrumental Visualization	3.37	0.79	Devising a Plan	3.35	0.51
Proactive Visualization	3.91	0.76	Carrying Out the Plan	3.44	0.51
Representative Visualization	3.94	0.75	Evaluating Results	3.70	0.53
Total	3.57	0.51	Total	3.56	0.40

Are scores of visualization tendency able to predict problem-solving ability?

Correlation analysis

A primary issue is whether visualization tendency is able to predict problem-solving ability. To address this issue, we have conducted correlation analyses between scores of visualization tendency and scores of problem-solving ability, as summarized in Table 2. As can be seen in the first row in the table, there is a significant positive correlation between visualization tendency and problem-solving ability, with Pearson's r's ranging from 0.41 to 0.51 based on two-tailed tests with p < .01. In addition, in the first column in Table 2, a significant positive correlation

can be seen between problem-solving ability and the five factors of visualization tendency, with Pearson's r's ranging from 0.33 to 0.57, also based on two-tailed tests with $p<.01$. However, there were no significant correlations between the Proactive Visualization factor and the process of understanding a problem, with $r = 0.170$, $p>.05$, as well as between the Proactive Visualization factor and the process of devising a plan, with $r =0.190$, $p>.05$.

Table 2. Correlation between visualization tendency scores and problem-solving ability scores

	Total of Problem-Solving Ability	Procedure of problem-solving				
		Understanding a Problem	Identifying the Cause of The Problem	Devising a Plan	Carrying Out the Plan	Evaluating Results
Total of Visualization Tendency	**0.59****	**0.46****	**0.48****	**0.41****	**0.47****	**0.51****
Generative Visualization	**0.50****	0.39**	0.41**	0.37**	0.42**	0.37**
Spatial–Motor Visualization	**0.51****	0.42**	0.39**	0.35**	0.41**	0.44**
Instrumental Visualization	**0.39****	0.40**	0.31**	0.28**	0.29**	0.30**
Proactive Visualization	**0.34****	0.17	0.27**	0.19	0.30**	0.36**
Representative Visualization	**0.33****	0.22*	0.34**	0.22*	0.21*	0.30**

* Correlation is significant at the 0.05 level (two-tailed).
** Correlation is significant at the 0.01 level (two-tailed).
$n = 101$

These results show different relationships between the various visualization factors' scores and problem-solving ability scores. Overall visualization was related to whole problem-solving processes. In addition, Generative and Spatial-Motor Visualization have correlations with problem-solving ability. These results provide strong support for the prediction that problem-solvers' reasoning such as structure

representation or pattern recognition for solving a problem can be related to problem-solvers' visual thinking. Moreover, these results show how patterns of human visualization might work differently according to the five factors of problem-solving ability.

Regression analyses

To further examine the relationships between scores of visualization tendency and problem-solving ability measures, we conducted a multiple regression analysis using the stepwise method to evaluate the prediction of problem-solving ability from overall factor scores for visualization tendency, as summarized in Table 3.

Table 3 shows that scores of visualization tendency were significant predictor variables for problem-solving ability scores; $F(2, 98)=25.21$, $R^2=0.35$, adjusted $R^2=0.34$, $p<.01$, indicating that visualization tendency can account for approximately 34% of the variance in problem-solving ability. Especially, Spatial–Motor Visualization ($B=0.18$, $\beta=0.35$, $p<.01$) and Generative Visualization ($B=0.22$, $\beta=0.33$, $p<.01$) were the significant factors of visualization tendency for predicting problem-solving ability scores ($F(2, 98)=25.21$, $R^2=0.35$, adjusted $R^2=0.34$, $p<.01$).

Table 3. Stepwise regression models based on factors of visualization tendency with problem-solving ability scores

Factors of visualization tendency	B	SE B	β
Spatial–Motor Visualization	0.18	.049	0.35**
Generative Visualization	0.22	.063	0.33**
$F(2, 98)=25.21$, $R^2=0.35$, adjusted $R^2=0.34$, $p<.01$			

Also, we conducted multiple regressions to determine which visualization tendency factors affected each phase of the problem-solving processes. Table 4 shows the significant factors of visualization tendency for predicting the scores of problem-solving processes. For the process of Understanding the Problem, Spatial–

Motor Visualization and Instrumental Visualization were the significant predictor variables: $F(2, 98)=16.10$, p<.01, $R^2=0.25$, adjusted $R^2=0.23$, Spatial–Motor Visualization's β=0.31, and Instrumental Visualization's β=0.29.

Table 4. Stepwise regression models based on factors of visualization tendency as predictor variables with scores in the phases of problem-solving as dependent variables.

The phases of problem-solving	Predictor variable	B	SE B	β
Understanding the Problem	Spatial–Motor Visualization	.225	.067	.313**
	Instrumental Visualization	.204	.065	.293**
	$F(2, 98)=16.10$, $R^2=0.25$, adjusted $R^2=0.23$, $p<.01$			
Identifying Cause of the Problem	Generative Visualization	.256	.069	.342**
	Representative Visualization	.146	.054	.248**
	$F(2, 98)=13.99$, $R^2=0.22$, adjusted $R^2=0.21$, $p<.01$			
Devising a Plan	Generative Visualization	.228	.091	.263*
	Spatial–Motor Visualization	.150	.070	.225*
	$F(2, 98)=10.48$, $R^2=0.18$, adjusted $R^2=0.16$, $p<.01$			
Carrying Out the Plan	Generative Visualization	.257	.087	.296**
	Spatial–Motor Visualization	.177	.067	.266**
	$F(2, 98)=15.00$, $R^2=0.23$, adjusted $R^2=0.22$, $p<.01$			
Evaluating Results	Spatial–Motor Visualization	.237	.070	.344**
	Generative Visualization	.186	.091	.207*
	$F(2, 98)=14.57$, $R=0.23$, adjusted $R^2=0.21$, $p<.01$			

For Identifying the Cause of the Problem, Generative Visualization and Representative Visualization were the significant predictor variables: $F(2, 98)=13.99$, $p<.01$, $R^2=0.22$, adjusted $R^2=0.21$, Generative Visualization β=0.34, Representative Visualization β=0.25. For the remaining processes—Devising a Plan, Carrying Out

the Plan, and Evaluating the Plan, Generative Visualization and Spatial–Motor Visualization were the significant predictor factors. The process of Devising a Plan showed the results $F(2, 98)=10.48$, $p<.01$, $R^2=0.18$, adjusted $R^2=0.16$, Generative Visualization $\beta=0.26$, and Spatial–Motor visualization$=0.23$. The process of Carrying out the Plan showed $F(2, 98)=15.00$, $p<.01$, $R^2=0.23$, adjusted $R^2=0.22$, Generative Visualization $\beta=0.30$, and Spatial–Motor Visualization $\beta=0.27$. Last, the process of Evaluating the Plan showed $F(2, 98)=14.57$, $p<.01$, $R^2=0.23$, adjusted $R^2=0.21$, Spatial–Motor Visualization $\beta=0.34$, and Generative Visualization's $\beta=0.21$. The visualization factors' scores accounted for approximately 16 to 23% of the variance in problem-solving ability measures. These results tell us that Generative Visualization and Spatial–Motor Visualization can be considered the major factors of college students' visual thinking ability in terms of their (significant) effect on problem-solving ability.

Does visualization tendency differ by problem-solving ability measure?

The analysis results revealed that visualization tendency scores are significantly related to problem-solving ability measures as predictor variables. Next, to examine whether problem-solving ability measures were significantly different by the level of visualization tendency, we conducted t-tests with visualization tendency (strong versus weak) and problem-solving ability measures, with an effect size based on $p < .05$.

The mean scores (and SDs) of problem-solving ability for the two groups are presented in the top row of Table 5. The groups differed significantly in problem-solving ability ($t=5.41$, $df=99$, $p<.01$, and it was revealed that the strong tendency group (M=3.74, SD=0.37) significantly outperformed the weak tendency group (M=3.35, SD=0.34). The effect size was large, with $d=1.07$. The third column of Table 5 lists the mean scores of problem-solving processes for the two groups. The overall mean rating of the strong tendency group was significantly greater than that

of the weak tendency group, with the results: Understanding a Problem (t=3.95, df=99, p<.01, d=0.74), Identifying the Cause of the Problem (t=2.85, df =99, p<.01, d=0.56), Devising a Plan (t=4.13, df =99, p<.01, d=0.83), Carrying Out the Plan (t=4.78, df =99, p<.01, d=1.07), and Evaluating Results (t=4.46, df =99, p<.01, d=0.86). The effect sizes for the significant are ranged from d=0.56 to d=1.07. Overall, the result that the strong tendency group outperformed the weak tendency group means that it is possible that a student who achieves a strong visualization tendency will be more likely to obtain a high score for problem-solving ability.

Table 5. The results of the t-tests for problem-solving scores between the strong- and weak-visualization tendency groups

Phases of Problem-solving	Level of Visualization Tendency	M	SD	t	d
Problem-solving ability	High	3.74	0.37	5.41**	1.12
	Low	3.36	0.34		
Understanding a Problem	High	4.00	0.49	3.95**	0.74
	Low	3.60	0.54		
Identifying the Cause of the Problem	High	3.74	0.43	2.85**	0.56
	Low	3.50	0.43		
Devising a Plan	High	3.53	0.48	4.13**	0.83
	Low	3.14	0.47		
Carrying Out the Plan	High	3.65	0.51	4.78**	1.07
	Low	3.21	0.41		
Evaluating Results	High	3.91	0.48	4.46**	0.86
	Low	3.48	0.50		

n = 53 (strong tendency group), 48 (weak tendency group)
**: p < .01

We conducted discriminant analysis between the two groups in order to identify the difference in problem-solving ability by scores of visualization tendency. There was a significant difference between groups, with Wilks' $\lambda=0.76$, $\chi^2=27.07$, $df=5$, and $p<.01$. The correlations between predictor variables and discriminant functions suggested that the strong tendency group was positively correlated with problem-solving ability ($r =0.54$), indicating that students with a higher score in visualization tendency were more likely to have a higher score in problem-solving ability. Meanwhile, the weak tendency group showed a negative correlation with problem-solving ability ($r =-0.59$), indicating that students with a low score in visualization tendency were less likely to have a high problem-solving score. Overall, the discriminant functions successfully predicted outcome for 71.3% of 101 cases, with accurate predictions being made 66.0% for the strong tendency group and 77.1% for the weak tendency group.

Conclusions and Discussions

Empirical contributions

This study showed a strong relationship between visualization tendency and problem-solving ability and found that visualization tendency as a degree of visual thinking is a predictor variable for problem-solving ability. Additionally, it turned out that Generative Visualization and Spatial–Motor Visualization as sub factors of visualization tendency were significantly influential factors throughout the phases of problem-solving. In detail, the study found that Instrumental Visualization and Spatial–Motor Visualization were significant predictors for the process of understanding the problem, while both Representative Visualization and Generative Visualization significantly affected the process of identifying the cause of the problem, and both Spatial–Motor Visualization and Generative Visualization were

influential predictor variables for the other three problem-solving processes.

Meanwhile, the study found that a student with a strong visualization tendency was more likely to have high problem-solving ability. This result showed a high effect size, d=1.12 for the significant difference at the level of visualization tendency. The discriminant analysis showed that respondents in the strong tendency group for visualization had a positive relationship (r =0.54) with problem-solving ability, while those in the weak tendency group had a negative relationship (r =−0.59). The discrimination of groups had a high variance of 71.3%, which means that the level of visualization tendency is an exact predictor of problem-solving ability.

Theoretical contributions

The first theoretical contribution of this study was that it revealed that college students' visualization tendency had a moderate relationship with problem-solving processes. In addition, it turned out that Generative Visualization and Spatial–Motor Visualization were significant predictor variables throughout the whole process of problem-solving. This means that students perceive, reason, and operate objects in a problem space while they solve a problem (Corter & Zahner, 2007; Cox, 1999; Jonassen & Hung, 2006; Mayer, 1994; Scaife & Rogers, 1996; Scheiter, Gerjets, & Catrambone, 2004; Sedlmeier, 2000; Sweller & Chandler, 1994).

Second, the research found that Proactive Visualization did not affect the processes of identifying a problem or devising a plan. The reason is that visualization depends on perceptions of physical objects rather than imagination and creativity. Last, it was seen that the five visualization tendency factors had low correlations with the process of devising a plan. It appears that type or level of knowledge has more influence on devising a plan than does visualization tendency.

There are also more specific results showing the different influences of visualization tendency factors on each process of problem-solving. First, Spatial–

Motor Visualization and Instrumental Visualization turned out to be significant factors for understanding and identifying a problem. That is, while students represent objects, events, and information internally by operating visually in a problem space, they identify and clarify them externally using visuals such as pictures, diagrams, figures, and so forth. Although the activation of Instrumental Visualization can be considered a natural, developmental phenomenon of human cognition, another possible interpretation is that students have learned how to externalize a problem using various visuals. More exposure to high-frequency and high-quality external visuals can help students more easily and quickly apply them to problem-solving.

Second, Generative Visualization and Representative Visualization were identified as significant factors for the process of identifying the cause of a problem. It appears that students analyze causes by integrating previous knowledge with internalized and externalized information from the process of identifying and clarifying the problem. Specifically, they derive or reproduce specific scenes or images from represented knowledge or information in order to analyze the cause. It can thus be inferred that students reason visually according to a variety of schemata on the basis of accumulated information, knowledge, contexts, and so forth.

Third, the results showed that Spatial–Motor Visualization and Generative Visualization were significant predictor variables in three processes of problem-solving: devising a plan, carrying out the plan, and evaluating results. It indicates that the complementary mechanisms of internalization and externalization may play an important role in problem-solving.

The final significant result is that students with strong visualization tendency have higher problem-solving ability. This supports previous research on the supportive roles of visualization in understanding a problem, recall and retention, and reasoning.

Practical contributions

The result revealed that Generative Visualization and Spatial–Motor Visualization affect every step of problem-solving. Therefore, educational methods need to be devised in order to facilitate the development of these visualization skills. More specific instructional suggestions are as follows.

First, a variety of verbal and visual information regarding a problem needs to be provided in order to foster Generative Visualization ability. Because Generative Visualization tends to help students reason a solution visually according to their experience perceiving objects throughout problem-solving processes, useful knowledge, example cases, and information should be provided to give students experience perceiving relevant physical objects, events, and the like, which are the fundamentals for inferring the most optimal solution. It appears that students' visual experience contributes to reducing cognitive load in devising solutions.

Second, visual thinking skills and strategies need to be offered during problem-solving, because the internal or external representation of a problem is very important at the beginning of the problem-solving process (Corter & Zahner, 2007). In general, visual thinking methods or strategies for the facilitation of Generative Visualization ability can be found in thinking strategies for creative problem-solving such as SCAMPER, brainstorming, the forced-connection method, morphological analysis, attribute listing, hits, highlighting, reverse brainstorming, and so forth. Furthermore, with the help of visuals such as diagrams, flowcharts, and concept maps, students more easily externalize complicated problems (Cuevas, Fiore, & Oser, 2002; Quintana, Krajicik, & Soloway, 2001).

Finally, both visual thinking strategies and visuals need to be used simultaneously for the reciprocal operation of internalization and externalization. They tend to reduce cognitive load and elaborate problem-solving solutions effectively and efficiently (Jonassen & Hung, 2006; Schwartz & Heiser, 2006; Sweller & Chandler, 1994). The simultaneous interaction between internal and external representation is

more likely to facilitate meta-cognition for problem-solving.

Limitations and future directions

One limitation of the present research is that the investigation was confined to college students. Further studies need to show how visualization tendency and its factors differ according to age, gender, level of visualization ability (perception, mental operation on two or three dimensional space) and so on. That is, the influence of students' individual characteristics on problem-solving ability in general and on each process of problem-solving needs to be explored.

In this study, self-report instruments were used to examine problem-solving ability in everyday life situations. However, both ability and process in problem-solving can differ by subject matters such as mathematics, science, music, arts, or some other area. Moreover, different types of problems exist in terms of structuredness, complexity, and dynamicity (Jonassen, 2004). Therefore, more various problem-solving contexts related to visualization tendency need to be taken into consideration in further studies.

Last, the visualization research presented here needs to be examined for correlations and causal relationships with not only problem-solving ability but also comprehension, spatial-perception ability, creativity, and the like. These efforts will contribute to supporting human teaching and learning by using scientific approaches based on experiential evidences.

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