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Divergence and convergence of mental forces of children in open and closed mathematical problems

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In this study we investigated relationships between convergent and divergent thinking with an emphasis on fluency, originality, flexibility and elaboration in the mathematical domain. A related purpose was to examine relationships between problem types in mathematical tasks. The math section of a performance-based assessment was used to assess 857 Grade 1 to 6 students' performance in the mathematical domain. Statistically significant correlations were found between divergent and convergent thinking, and between convergent thinking and the components of divergent thinking. Also, this study provided evidence for the construct validity of the Problem Continuum Matrix (Schiever and Maker, 1991, 1997). Correlations between problem types varied according to the proximity of the types to each other.

Mathematics, convergence, divergence, creativity, gifted

INTRODUCTION

One mode of effective problem solving is to give up the old habit of thinking and try an unconventional mode of thinking. This method of problem solving involves the ability to think in a flexible fashion. Flexible thinking involves the ability to shift cognitive functioning from common applications to the uncommon; namely, breaking through cognitive blocks and restructuring thinking so that a problem is analysed from multiple perspectives. The process of flexible thinking includes both divergent and convergent thinking provided that a problem solver works on multiple solutions, as well as one single solution during the course of problem solving.

Traditionally, divergent thinking is defined as the generation and application of many different ideas to solve a given problem and is considered a good predictor of creative performance (Runco, 1990). The main focus in divergent thinking is on the quantity and quality of ideas or responses generated by the problem solver in response to prompts (Guilford, 1967). The quality and quantity of responses are evaluated based on fluency (How many ideas?); flexibility (How diverse are the classifications of ideas?); originality (How unique are the ideas?); and elaboration (How detailed are the ideas?). Divergent thinking assessments have open-ended questions or tasks to stimulate a variety of ideas.

Convergent thinking is the mental process of deriving the best or correct solution from available information. The task of the problem solver is to go back to her/his stored information (Puccio, 1998) and to make that information meaningful or useful through appropriate mental information processing. A problem sometimes requires only the application of algorithms for solutions. Some intelligence tests and academic achievement tests are good examples of ways to measure convergent thinking; they contain well-defined problems that usually have one correct answer.

Although both divergent and convergent thinking produce ideas, qualitative and quantitative differences can be found between the end products of each type of thinking. Divergent thinking often results in variability in production while convergent thinking results in singularity in production (Cropley, 1999).

Cropley (1992, 1999) further elaborated the distinction and relationship between divergent and convergent thinking. According to Cropley, early researchers in creativity tended to separate both types of thinking and considered them as functions of giftedness in different forms. He also discussed that gifted students produce both singular (convergent thinking) and varied (divergent thinking) information. However, a combination of thinking processes is necessary for novel production. Two approaches, "threshold models" and a "style approach" have been devised to explain the interaction of convergent and divergent production.

The *threshold model* was developed to explain the function of level of ability on divergent and convergent thinking. As the level of ability increases to produce singular information, the possibility of variability in production increases accordingly. Therefore, any movements in ability toward or away from the threshold directly affect the quality and quantity of information produced through divergent thinking mechanisms. In this approach, a certain level of ability is necessary for novel production. On the other hand, the *style approach* elucidates the interaction between the two forms of thinking through cognitive strategies. According to this approach, neither type of thinking influences the other. What produces singularity and variability are the cognitive strategies and mechanisms. In short, both approaches have as a central concept the interaction between two thinking forms either in levels of cognitive abilities or types of functions of the mind.

Problem Types for Measuring Divergent and Convergent Thinking

The use of divergent or convergent thinking in problem solving depends mainly on the types of problems chosen or presented, that is having open or closed problem situations. Problems can be classified into different categories. Most problems are classified into the categories of well-defined (open) and ill-defined problems (closed) (Jausovec, 1994). Howard (1983) identified two distinctive characteristics of well-defined problems that distinguish them from ill-defined problems. First, the goal is clearly specified in well-defined problems while the goal is unclear in ill-defined problems. Second, the problem statement in well-defined problems contains specified, clear and enough information necessary for solutions. In the case of ill-defined problems, information in the problem statement is not clear, or the relevance of information to the problem solution is not specified. Howard proposed that these distinctive characteristics represent a continuum, according to which problems can be classified into more categories.

Another classification was proposed by Getzels and Csikszentmihalyi (1976). Their classification is based on the triangle of problem statement, method and solution. The type of problem varies according to the specificity of the problem statement, method and solution to both problem presenters (for example, teachers) and problem solvers (for example, students). They identified three problem types: the first two are well-structured (closed), and the third is ill-structured (open); that is, the problem is not defined and the solution is unknown. In the third, the task of the problem solver is first to find or define the problem and then to develop method(s) to solve the problem.

Problems can be classified into more varied categories according to problem spaces, and cognitive processes and types of knowledge used during problem solutions. However, the distinction between ill-defined problems and well-defined problems is not clear enough to be useful in experimental research and in education for instructional purposes. Building on Getzels and Csikszentmihalyi's work, Schiever and Maker (1991, 1997) identified two additional problem types that extended the original classification. The new classification is called "Problem

Continuum Matrix." Table 1 shows the essential characteristics of the matrix. There are five problem types in this classification, and they are more specific. Inspection indicates that the number of problems is not limited to five; rather it is a continuum. That is that more specific problem types can be generated based on the matrix.

Table1. Problem Types

Problem Type	Problem		Method		Solution	
	Presenter	Solver	Presenter	Solver	Presenter	Solver
I	K	K	K	K	K	U
II	K	K	K	U	K	U
III	**K**	**K**	**R**	**U**	**R**	**U**
IV	**K**	**K**	**U**	**U**	**U**	**U**
V	U	U	U	U	U	U

K=Known, U=Unknown, R=Range (A variety of methods and solutions are available for a problem and only the problem presenter is aware of them).
Highlighted (bold) problem types were identified by Schiever and Maker (1991, 1997).

Creativity usually is assessed using Problem Type IV, but sometimes is assessed with the more structured Type III, and sometimes with the unstructured Type V Problem situation, often called "problem-finding." Type I and II problems also are used to assess insight problems. An assessment tool that enables us to measure performance on all these varied types of problems can give us insights into the problem solving abilities of individuals. Information gained from this assessment then can be used to nurture students' problem solving abilities and their creativity.

The DISCOVER Assessment Model

The Discovering Intellectual Strengths and Capabilities while Observing Varied Ethnic Responses (DISCOVER) Assessment Model was designed to assess the problem solving abilities of children and youth in domains of intelligence. The assessment battery contains all five types of problems to provide introspective profiles of students' convergent and divergent performances.

The math section of the assessment contains problem Types I, II, III, and IV. Individual scores in the mathematical tasks of the DISCOVER Assessment are given in two categories: accuracy and the use of mathematical concepts in answers. The total accuracy score is the number of correct responses to all problem types. While the accuracy scores for problem Types I and II (structured, one right method and one right solution) are indicative of convergent performance, the accuracy of responses in problem Types III and IV (many correct methods and many possible solutions) reflects fluency.

Concept scores are based on evidence of understanding and meaningfully using mathematical concepts. This includes a variety of operations and strategies the individual applies in solving math problems, such as commutative (for example, 10+8+10=28; 8+10+10=28) and associative properties (for example, [5+5]+8=18; 5+[5+8]=18) as well as making unique problems (for example, story problems, symbolic representations, use of algebraic notations, fractions, decimals, and/or Roman Numerals), and the recognition and creation of shapes and patterns. Concept scores are derived from responses to problem Types III and IV. They measure the flexibility, originality, and elaboration components of divergent thinking. For example, the variety of operations that a person uses to get the same correct answer contributes to that person's flexibility scores. Given the answer 13, we can get it in many different ways such as 4+9, 23-10, $13 \div 1$, $(13x1) \div 1$, and so forth.

RESEARCH RATIONALE

Research on divergent and convergent thinking has focused on fluency, originality and flexibility mostly in linguistic, artistic and spatial domains (Borland, 1986; Guilford, 1984; Runco, 1986, 1991; Runco and Albert, 1989; Wyver and Markham, 1999; Torrance and Saburo, 1979). The relationship of convergent to divergent thinking in mathematical domain still remains unclear. Divergent and convergent thinking play a major role in mathematical discoveries in that a problem solver often has to try many mathematical demonstrations if one does not work. Sometimes, only one method can lead to a correct solution as happens in mathematical deductions. Therefore, divergent and convergent thinking and their relationship in math problem solving situations merit further research.

The purpose of our study was to explore how performance on convergent tasks relates to performance on divergent tasks in mathematics. Further, the relationships between problem types in the math section of the DISCOVER Assessment were investigated. The following research questions guided the study:

1. How does student performance on convergent tasks relate to performance on divergent tasks in the mathematical domain?
2. How does student performance on fluency and OFE (Originality, Flexibility and Elaboration) relate to performance on convergent tasks in the mathematical domain?
3. What relationships, if any, exist between Problem Types?

METHOD

Participants

Data for the study were collected as part of a larger study of the DISCOVER Assessment and Curriculum models. Participants were Grade 1 to 6 students assessed in the schools participating in the DISCOVER Project. All participating schools were located in the southwest region of the United States. The total number of students was 857 from four schools, as presented in Table 2. The ethnic background of the population varied from school to school. School A was composed of 99 per cent Navajo, school B was 98 per cent Hispanic, school C was 50 per cent Caucasian and 50 per cent African American, and school D was mixed, including Hispanic, Caucasian, African American, and Yaqui Indian.

Table 2. Number of participants in each school and grade level

			Grade				
School	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
A	46	34	52	58	54	-	244
B	47	40	37	45	38	-	207
C	32	-	29	33	40	28	162
D	45	60	46	39	54	-	244
Total	170	134	164	175	186	28	857

Instrument

The DISCOVER Assessment was used to asses students' divergent and convergent thinking. The assessment tool has been used with diverse populations in the United Sates, as well as abroad. The reliability ranges from 0.92 to 1.00 when expert observers do the assessment. Novice observers' agreement with an expert ranges from 0.47 to 0.92 (Maker, 2001). Studying the concurrent validity, Almegta (1997) found that DISCOVER math total scores and accuracy scores were correlated significantly with math achievement ($r=0.335$, $p<0.05$ and $r=0.325$, $p<0.05$) but concept scores were not ($r=0.306$, ns). Sarouphim (2000) found significant correlations between the Raven Progressive Matrices and math ($r=0.35$, $p<0.01$) sections of the DISCOVER Assessment. Furthermore, Sak and Maker (2003) investigated the predictive validity of the assessment through examining kindergarten students' performance in the logical mathematical domain as measured by the DISCOVER Assessment and their academic achievement in 3rd, 5th and 6th Grades as measured by Stanford 9 Achievement Test and Arizona's Instrument to Measure Standards (AIMS). In their study, logical mathematical intelligence accounted for 29 per cent of the overall variance in Stanford 9 Math ($p=0.033$) and 39 per cent in AIMS Math ($p=0.003$) in 3rd Grade. In 5th and 6th Grades, students gifted in logical mathematical intelligence scored significantly higher in Stanford 9 Math ($F= 6.14$, $p<0.01$) and AIMS Math ($F= 4.15$, $p<0.01$), and had significantly higher grades in 6th Grade math ($F= 4.50$, $p<0.01$) when compared to their counterparts. Also, students gifted in logical mathematical intelligence had higher grades in 6th Grade science ($F= 5.95$, $p<0.01$).

Procedure

The DISCOVER Assessment has different forms for grades K-2, 3-5, 6-8, and 9-12. Either the classroom teacher or a trained DISCOVER observer can administer the math portion of the DISCOVER Assessment. For this study, the classroom teachers administered the assessment. First, they gave each student one worksheet and one blank sheet of paper. They read standard instructions and clearly wrote examples for each section on the board so that students could understand the task. The use of explicit instructions has been found to significantly enhance divergent production (Runco and Okuda, 1988).

In the first part of the assessment (Problem Type I), students solved math problems that were clearly defined. Students knew what operations or methods to use, and were asked to compute one correct answer for each problem.

In the second part (Problem Type II), teachers instructed students in how to solve *"magic square"* problems, and then worked a sample problem with them. Students then solved the problems. Grade 3 through 6 students created their own *"magic squares"*, placing numbers and applying math operations.

In the third part (Problem Type III), students made correct addition, subtraction, multiplication, and division problems using only the three numbers given in each problem. Only addition and subtraction problems were given to 1st and 2nd Grade students. The 6th Grade sheets had fractions and decimals as well.

In the fourth part (Problem Type IV), students wrote problems that had a certain number as the answer (the answer for each grade was given). Students were prompted to write as many problems as possible that would equal the given number. Examples using a different final number were provided to make certain students understood the task.

After the administration, a DISCOVER team member scored students' solutions using standard criteria. Scoring was based on several criteria such as correctness, variety, and originality of responses. One point was given for each correct answer in all problem types. Two points were given for the use of two operations, understanding of commutative and associative properties, related facts, inverse operations, and creative use of numbers anywhere within the problems. Four points were given for the use of three operations, and six points were given for using all four types of operations. Five points were given for both clear use of strategy and unique problems. For scoring magic squares, one point was given for correct squares except the final answer. Two points were given for an entire magic square that was correct. Also, three points were given for the student-created correct magic square.

Data Analysis

The researchers analysed convergent, accuracy, and concept scores of 857 students in the math section of the DISCOVER Assessment. The Pearson Product Moment Correlation was calculated through SPSS to determine relationships between divergent and convergent scores, and fluency and OFE scores. Coefficients of determination were calculated to find overlaps between variables. Then, “r” values were converted into “z” values to test the significance of differences between correlation coefficients.

RESULTS

Divergent and Convergent Thinking

The relationship between divergent and convergent thinking in the mathematical domain was investigated using the Pearson product-moment correlation coefficient. Preliminary analyses were performed to ensure that no violation of the assumptions of normality, linearity and homoscedasticity occurred. As shown in Table 3, a moderate, positive correlation was found between convergent and divergent thinking ($r=0.49$; $n=788$; $p<0.01$). Further, the analysis showed a strong, positive correlation between OFE (originality, flexibility, and elaboration) scores and convergent scores ($r=0.51$; $n=810$; $p<0.01$). Also, fluency scores were correlated with convergent scores moderately in a positive direction ($r=0.44$; $n=796$; $p<0.01$). Additionally, no statistically significant difference in the strength of the correlations was found between convergent scores, fluency scores, and OFE scores ($z=1.60$; $p>0.05$). However, OFE explained more of the variance in convergent performance than did fluency. The coefficient of determination indicated that OFE and convergent performance had a 26.98 per cent shared variance while fluency and convergent performance had a 20.16 per cent shared variance. Also, divergent performance and convergent performance had a 24.70 per cent shared variance.

Table 3. Intercorrelations between convergent, divergent, fluency, and OFE in mathematical tasks

n=788	Divergent	Convergent	OFE*	Fluency
Divergent	--	.49**	.86**	.97**
Convergent		--	.51**	.44**
OFE			--	.72**
Fluency				--

* OFE consists of originality, flexibility and elaboration scores.
** Correlation is significant at the 0.01 level (2-tailed).
Divergent performance is the sum of OFE and fluency scores for Problem Types III and IV *Problem Types*

Correlations between all problem types were statistically significant, positive, and moderate, as presented in Table 4. All correlations were significant at the 0.01 level. A moderate, positive correlation existed between Problem Types I and II ($r=0.49$; $p<0.01$). Similarly, the correlation between Problem Types III and IV was moderate in a positive direction ($r=0.46$; $p<0.01$). The correlations between Problem Type III and I and II ($r=0.41$; $p<0.01$; $r=0.39$; $p<0.01$) were stronger than those between Type IV and I and II. ($r=0.39$; $p=0.01$; $r=0.36$; $p<0.01$). The coefficients of determination indicated 24.80 per cent shared variance or overlap between Problem Types I and II, and 21.34 per cent between Types III and IV.

Table 4. Correlations between problem types

Problem Types	I	II	III	IV
I	--	.49*	.41*	.39*
II		--	.39*	.36*
III			--	.46*
IV				--

* Correlation is significant at the 0.01 level (2-tailed).

In addition to correlations and comparisons between all problem types, the relationships between Types III and IV fluency and OFE performances were investigated using correlational procedures. Correlations varied from moderate to strong between fluency and OFE performances in these problem types, shown in Table 5. The correlation between Problem Type III Fluency scores and

OFE scores was strong (r=0.85; $p < 0.01$). Similarly, the correlation between Type IV fluency and OFE scores was strong (r=0.65; $p<0.01$). Type III fluency scores were correlated with Type IV fluency and OFE scores moderately in a positive direction (r=0.40; <0.01 and r=0.47; $p<0.01$). Also, Type III OFE scores were correlated with Type IV fluency and OFE scores moderately in a positive direction (r=0.39; $p<0.01$; r=0.48; $p<0.01$).

Table 5. Intercorrelations between performance in problem types in mathematical tasks

Problem Types	I	II	III Fluency	III OFE*	IV Fluency	IV OFE
I	--	.49**	.37**	.41**	.36**	.39**
II		--	.37**	.38**	.32**	.37**
III Fluency			--	.85**	.40**	.47**
III OFE				--	.39**	.48**
IV Fluency					--	.65**
IV OFE						--

*OFE consists of Originality, Flexibility and Elaboration scores.
** Correlation is significant at the 0.01 level (2-tailed).Discussion and Conclusion

In this study, we investigated relationships between divergent and convergent thinking, and also between fluency, originality, flexibility and elaboration and convergent thinking in the mathematical domain. Relationships between Problem Types in mathematical tasks also were studied. A moderate relationship exists between divergent and convergent thinking. Likewise, a moderate relationship exists between convergent thinking and the components of divergent thinking: fluency, originality, flexibility and elaboration (OFE), in tasks that require basic mathematical knowledge and creative thinking in this domain. Overlap between these thinking types ranged from approximately 20 to 27 percent. Interestingly, OFE explains more of the variance (26.98%) in convergent thinking performance than does fluency (20.16%). However, this difference was not found to be statistically significant. More research is needed to explain this complex relationship, not only in the mathematical domain but also in other areas.

Although divergent and convergent thinking in children is correlated, we still do not know the causal relationship. A completely different variable not included in our study might cause or explain the overlap between divergent and convergent thinking. At the beginning of the paper, two approaches, ‘a threshold model’ and ‘a style approach’ were presented as possible ways to explain the complex relationship between divergent and convergent thinking. If we take into account the ‘threshold model’, the overlap between the two variables might be explained by general intellectual ability. On the other hand, the existence of a significant but not very strong correlation between the two variables indicates a distinction between them.

The findings can be interpreted to mean that divergent thinking and its mechanisms, fluency and OFE, have impact both on children’s mastery of content areas and on academic achievement in the mathematical domain. Nevertheless, we do not recommend that this interpretation be applied in other domains of ability and knowledge. Recent studies (Baer, 1998; Bamberger, 1990; Han and Marvin, 2002; Lubart, 2003; Plucker, 1998) have demonstrated that creativity is domain specific rather than general across diverse domains, and researchers have further suggested that creativity in one domain does not predict creativity in another domain. In light of these results, creativity and particularly its components in school-age children should be assessed in specific domains. Such assessment provides estimates of the potential for current and future academic achievement of students, as well as their likely creative contributions to fields that require mathematical skills.

Another significant finding of this study was the relationships that exist between Problem Types. The researchers looked at associations between four of the Problem Types and explored the moderate and positive correlation. Moreover, support for the construct validity of these Problem Types was found – although all types are correlated with each other, the strength of correlations between types, as shown in Table 6, is based on the proximity of Problem Types to each other. For instance, Type I has a stronger correlation with Type II (r= 0.49) than it does with Types III and IV (r= 0.41; 0.39). In the same way, the relationship between Types II and III (r= 0.39) is stronger than that between Types II and IV (r= 0.36). The more distant two problem types are from each other, the lower the correlation between them, a fact that provides validation for the problem continuum. Based on this finding, one can say that various problem types challenge the mind in differing ways. Therefore, integration of all problem types into the curriculum and assessment systems can improve the education of school-age children.

Table 6. Mean scores of participants on divergent, convergent, OFE, fluency, and each problem type

	N	Mean	SD
Divergent	797	21.32	18.88
Convergent	843	8.91	3.96
Fluency	806	13.50	13.78
OFE	822	7.51	6.28
PT I	853	5.40	2.08
PT II	847	3.47	2.51
PT III fluency	839	3.47	3.32
PT III originality	852	2.91	3.25
PT IV fluency	821	9.84	12.03
PT IV originality	825	4.53	4.00

SD- Standard Deviation; PT- Problem Type

The relationship of Problem Type V to the others in the Problem Continuum remains unanswered even though we know that it is less structured than Type IV. Moreover, other researchers (Bransford and Stein, 1984; Getzels and Csikszentmihalyi 1976; Runco and Okuda 1988) discussed "discovered problem situations" and distinguished between "problem identification" and "problem definition" by saying that the former is closer to "problem discovery." An interesting new study would be to examine the double facets (identification and definition of problems) of Type V problems in the mathematical domain, as well as in other domains of human intellect. Therefore, a possible future study of the Problem Types might include the investigation of relational proximity of Problem Type V to the other types by "problem identification" and "problem definition."

Ideally, the present research will serve as an illuminating study for the systematic and theory-based development of problems in designing curriculum, instruction and assessment in mathematics. Accordingly, this can make valuable contributions to the education of the mathematically creative, as well as all types of students. Future research can focus on impacts of different ethnic, cultural, and environmental contexts on divergent thinking and its components (for example, fluency, originality, flexibility, and elaboration) in the mathematical domain. Likewise, any developmental trends in creative thinking in the mathematical domain (specifically fluency and originality of behaviours) of children by both age and grade level, and even culture, should be examined.

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