International Education Journal, 2007, 8(2), 187-203.
ISSN 1443-1475 © 2007 *Shannon Research Press*.
http://iej.com.au

Gender differences in mathematical problem solving patterns: A review of literature

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A large body of literature reports that there are gender differences in mathematical problem solving favouring males. Strategy use, as a reflection of different patterns in mathematical problem solving between genders, is found to be related to cognitive abilities, together with psychological characteristics and mediated by experience and education. Many complex variables including biological, psychological and environmental variables are revealed to contribute to gender differences in mathematical problem solving in some specific areas. This article suggests that the combined influence of all affective variables may account for the gender differences in mathematical problem solving patterns.

gender differences, mathematical problem solving,
mathematical problem solving patterns, school students

In the past few decades, research has repeatedly reported gender differences in mathematics performance on a number of standardised mathematics tests such as the Scholastic Assessment Test-Mathematics (SAT-M) (Gallagher, 1990, 1992; Gallagher and DeLisi, 1994; Hyde, Fennema, and Lamon, 1990; Royer, Tronsky, Chan, Jackson and Marchant, 1999; Willingham and Cole, 1997). The test scores on these standardised tests have been regarded as an important measure of abilities to do mathematics problems (Casey, Nuttall, Pezaris, and Benbow, 1995; Halpern, 2000; Stumpf and Stanley, 1998). But results from these studies are not consistent: some found that males generally outperformed females on mathematical tasks (for example, Maccoby and Jacklin, 1974; Fennema and Carpenter, 1981; Halpern, 2000); some showed different sizes of gender differences with respect to types of mathematical tasks (for example, Voyer, Voyer, and Bryden, 1995). Hyde, et al. (1990) suggested that there was very small or null gender difference in mathematics performance on these tests. Caplan and Caplan (2005) even argued that the link between gender and the mathematics performance was very weak. Can test scores measure the real differences in cognitive abilities and abilities to solve mathematical problems between females and males?

Reviews of research led to the conclusions that there were gender differences in mathematical problem solving that favoured males based on the fact that male samples outperformed female samples in their studies (for example, Benbow and Stanley, 1980, 1983; Benbow, 1988; Casey et al., 1995; Gallagher and DeLisi, 1994; Royer, et al., 1999). However, these conclusions were often limited to an atypical population, normally talented or highly-motivated or college bound students, and relying on the selection of measures and the particular experimental situations (Caplan and Caplan, 2005). These conclusions were even sometimes challenged by the opposite evidence found among these high-ability populations. For example, Pajares (1996) found that gifted girls outperformed gifted boys in mathematical problem solving. Do the conclusions drawn from these highly selected populations reflect the real situation of a more general population? In addition, if gender differences do exist in mathematical problem solving, whatever they are, would there be any different patterns of mathematical problem solving between genders? And what are they if there are any?

Problem solving is the foundation of much mathematical activity (Reys, Lindquist, Lambdin, Smith, and Suydam, 2004). It is so important that the National Council of Teachers of Mathematics (NCTM) has identified it as one of the five fundamental mathematical process standards[1] (NCTM, 2000). Therefore, to find gender differences in mathematical problem solving patterns if any, to investigate these patterns from different perspectives, and thus to link to educational practice, would have significant consequences for educators.

My efforts started with finding factors that contributed to gender differences in mathematical problem solving, and then moved to biological, psychological, environmental perspectives, in order to find gender specific patterns of mathematical problems solving and possible explanations of their existence. However, research related to this issue was numerous but far to be systematic. Evaluating the related works that have been done and then addressing new directions for future research are therefore very difficult. This article has included several relevant studies to try to uncover answers to the questions mentioned before and to identify possible directions for future research.

MATHEMATICAL PROBLEM SOLVING: WHAT IS IT?

Mathematical problem solving is a complex cognitive activity. Some mathematical literature described mathematics problem solving as several separate activities such as doing word problems, creating patterns, interpreting figures, developing geometric constructions and proving theorems (Willson, Fernandez and Hadaway, 1993). While Polya's theory (Polya, in Willson, Fernandez and Hadaway, 1993) defined mathematical problem solving as a process that involved several dynamic activities: understanding the problem, making a plan, carrying out the plan and looking back The latter definition is applied to the discussion in this review.

Reitman (1965) described a problem solver as someone who received information and a goal without an immediate means to achieve the goal. In order to achieve the goal, the mathematical problem solver must develop a base of mathematics knowledge and organise it, create an algorithm and generalise it to a specific set of applications, and use heuristics (strategies, techniques, shortcuts) and manage them (Willson, Fernandez and Hadaway, 1993). Two types of thoughts: spatial inductive thought and verbal-logical deductive thought are both believed to be important to mathematical problem solving (Battista, 1990; Tartre, 1993). During the process, students might apply a number of general strategies such as a solution rubric, a logical-mathematical reasoning, a trial-and-error approach and an outright guess to derive answers on mathematical problem solving tests (Gallagher, DeLisi, Holst, McGillicuddy-DeLisi, Morely and Cahalan, 2000). Mayer (2003) divided mathematical problem solving into four cognitive phases: translating, integrating, planning and execution. Royer and Garofoli (2005) classified them into two stages: representation of a problem and solving the problem. Similarly, Montague (2006) defined mathematical problem solving as a process involving two stages: problem representation and problem execution. Both of them regarded representing the problem successfully as the basis for understanding the problem and making a plan to solve the problem. Specifically, Rocha, Rocha, Massad and Menezes (2005) indicated that coordination among "different neuron assemblies" (p.369) of related brain areas was essential to the solution to arithmetic problems.

As a conclusion, a mathematical problem solver not only required cognitive abilities to understand and represent a problem situation, to create algorithms to the problem, to process different types of information, and to execute the computation, but also had to be able to identify and manage a set of appropriate strategies (heuristics, techniques, shortcuts etc.) to solve the problem.

STRATEGY USE AS A RELECTION OF GENDER DIFFERENCES IN

[1] The five fundamental mathematical process standards: problem solving, reasoning and proof, communication, connections, and representations (NCTM, 2000).

MATHEMATICAL PROBLEM SOLVING PATTERNS

Hyde et al.'s (1990) meta-analysis of 100 studies suggested that gender differences in mathematics performance were small but gender differences in mathematical problem solving with lower performance of women existed in high school and in college. Many studies also pointed out the existing of gender differences in mathematical problem solving (Linn and Petersen, 1985; Ben-Chaim, Lappen and Houang, 1988; Tartre, 1990, 1993; Royer et al., 1999; Gallagher, et al., 2000). Many factors such as cognitive abilities, speed of processing information; learning styles, socialisation were suggested to have contributions to gender difference in mathematical problem solving (for example, Duff, Gunther, and Walters 1997; Kimball 1989; Linn and Petersen, 1985; Maccoby and Jacklin, 1974; Royer, et al., 1999). Based on these findings, we may assume that females and males have different patterns of mathematical problem solving. Since many mathematical problems on standardised tests are multi-step and require some systematic approach, students could arrive at a correct solution by choosing and combining a set of appropriate strategies. Strategy flexibility is important for successful performance on standardised tests such as the SAT-M (Gallagher et al, 2000). Only focusing on test sores might not reveal gender differences in problem solving patterns, investigating gender differences in strategy use might shed some light on researching gender patterns of mathematical problem solving. In this section I include some relevant studies that posited some hypotheses on students' strategy use from different perspectives, to try to compare different patterns of mathematical problem solving between female and male students.

Some research studies have reported gender differences in strategy use among elementary school students (Carr and Jessup, 1997; Carr, Jessup and Fuller, 1999; Carr and Davis, 2001; Fennema, Carpenter, Jacob, Frank, and Levi, 1998). First-grade girls were more likely to use a manipulative strategy and first-grade boys were more likely to use a retrieval strategy to solve mathematics problems (Carr and Jessup, 1997). Carr and Davis (2001) found that during the free-choice session of their study, girls and boys showed different preferences for strategy use to achieve the solution, which replicated the earlier findings of Carr and Jessup (1997); while during the game condition that constrained the types of strategies children used, boys showed the same ability as girls to use a manipulative strategy to calculate solutions, but girls were not as able as boys in the use of a retrieval strategy. Fennema et al. (1998) suggested girls tended to use more concrete strategies and boys tended to use more abstract strategies and that elementary school boys tended to be more flexible in employing strategies on extension problems than elementary school girls. Their study also found girls chose to use more standard algorithms than boys at the end of Grade 3. However, there were no gender differences in the group whose members had used *invented algorithms*[2] in the earlier grades.

Gender differences in strategy use were evident among secondary school students (Gallagher and Delisi's, 1994; Gallagher et al, 2000). Tartre's (1993) suggested that high school boys tended use a "complement" (p.52) strategy to solve problems involving three-dimensional figure. High school girls tried to use more writing to solve problems requiring a written strategy. Studies by Gallagher and her collaborators (Gallagher and Delisi, 1994; Gallagher et al, 2000) reported that among high school high-ability students there was no overall gender difference in the numbers of correctly answered items on the SAT, but under different situations, females and males approached mathematical problems by using different strategies.

> Gender differences were evident in successful patterns and in strategy use on conventional and unconventional problems…female students were more likely than male students to correctly solve "conventional" [3] problems (by) using algorithmic

[2] *Invented algorithm* is used by Fennema et al (1998) to identify strategies that involved abstract procedures children construct to solve multi-digit problems. It is distinct from those strategies with automatized quality.

[3] Gallagher (1990, 1992) classified many of the problems on the SAT-M into two categories: conventional problems are those problems that can be solved by familiar algorithms, which are normally textbook-problems;

> strategies; male students were more likely than female students to correctly solve "unconventional" problems (by) using logical estimation and insight. (Gallagher et al., 2000, p.167)

Related to Cognitive Abilities

Researchers have made a point that there is a relationship between the levels of student's abilities and strategy choice and efficiency (Lohman and Kyllonen; Kyllonen, Lohman and Snow; Kyllonen, Lohman and Woltz; Wendt and Risberg, in Burin et al., 2000). Higher ability students tended to solve problems by using more spatial processes, while the others tried to solve problems in a more analytical way. Tartre (1990, 1993) suggested that females with high spatial orientation (SO) skills were assumed more than high SO males to be able to integrate spatial and analytic or language skills to successful problem solution. Tartre also found that low SO males were found to be able to use the verbal hint effectively to help solving problems; but low SO females needed help more often and did not always use it successfully. It can be concluded from Tartre's study that the gender differences in strategy use during mathematical problems solving fall into two classes: (a) on one hand, gender difference within groups with high-spatial level skills arose through the ability to integrate many problem-solving strategies, with which females did better than males; (b) on the other hand, gender difference within groups with low-spatial level skill arose from the ability to use other skills to compensate, in which males outperformed females.

The discrepancy between spatial and verbal abilities also affected both females' and males' strategy use. Since many mathematical problems could be solved either by a spatial approach or by a verbal approach or by both of them, the discrepancy between spatial and verbal abilities would influence how students approached mathematical solutions (Krutetskii, 1976). For example, a student with high spatial ability and low verbal ability might try to use more spatial strategies to solve mathematical problems, while students high or low in both abilities might be more variable in strategy use (Battista, 1990). Therefore, if male and female students were discrepant in strengths and weaknesses of their spatial and verbal abilities, they would solve mathematical problem differently. A different ratio in the use of spatial to verbal skills (Maccoby and Jacklin, 1974), which in turn would influence students' problem solving abilities and strategies (Battista,1990), might create different patterns of mathematical problem solving between the two genders.

Fennema and Tartre (1985) conducted a three-year longitudinal study among middle school students (Grade 6 to Grade 8) in order to examine how students with discrepant spatial visualisation (SV) and verbal skill solved mathematical problems. The samples were divided into four groups: high SV/ low verbal males, high SV/ low verbal females, low SV/ high verbal males, and low SV/ high verbal females. Each participant was interviewed during each year and every time they were required to solve mathematics problems by drawing pictures and then to explain why they did so. In this study, no significant difference was found among groups in ability to solve mathematical problems, but differences in patterns of problem solving were detected: high SV/ low verbal groups tried to translate more information into pictures to solve problems, while low SV/high verbal groups tended to respond to problems by providing more relevant verbal-information. A large difference was also found within the female groups in terms of how much help was needed: the low SV/ high verbal females needed the most help to complete a picture to help solving problem, while the high SV/ low verbal females needed the least help. But the difference between the two male groups in this respect was small.

Battista (1990) conducted a study among 145 high school geometry students from middle-class communities. This research examined the role that spatial visualisation and verbal-logical thinking played in gender differences in geometric problem solving in high school. The findings

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unconventional problems are those problems that can be solved by using of logical estimation or insight or usual using of familiar algorithms, which are not presented frequently in textbooks.

suggested that males and females differed in the level of discrepancy between spatial and verbal abilities. The discrepancy between spatial and verbal skills was related to geometric problem solving for both genders. In addition, this study indicated that males with greater "discrepancy of spatial visualisation over verbal-logical ability" (Battista, 1990, p.57) were more likely to use visualisation strategies than to use drawing strategies in problem solving. However this conclusion only held for males, in another words, the discrepancy between spatial and verbal abilities do not influence females' strategy use in geometric problem solving.

Interfered with Psychological Characteristics

However, not every researcher shares the opinion that strategy choice and strategy efficiency is determined by the level of ability. Burin et al. (2000) found that there was no such a relationship at least on visualisation tasks. So why do females and males develop different strategies if there is no such a relationship? There are also some other considerations.

Gallagher et al. (2000) suggested that males tended to be more flexible than females in applying solution strategies. Kessel and Linn (1996) and Gallagher (1998) reported that females were more likely than males to adhere to classroom-learned procedures to solve problems, so they might be less likely to use shortcuts and estimation techniques for solving unfamiliar and complex problems quickly. Meyer, Turner and Spencer (1997) reported that "challenge avoiders"[4] were more likely than "challenge seekers" to use surface strategies which required minimal processing of information to solve problems. Carr et al. (1999) found that first-grade boys' strategy use was related to perception of adults' attitudes toward various strategies and teachers instruction, while this relationship was not applicable to first-grade girls' strategy use. Quinn and Spencer (2001) suggested that the interference of stereotype threat with females' ability influenced females' selection of problem-solving strategies.

This evidence discussed above indicates that strategy use in mathematical problem solving may be influenced by learners' psychological characteristics.

Mediated by Experience and Education

Many researchers suggested that mathematical problem-solving strategies responded to training (for example, Hyde et al., 1990). A meta-analysis (in Hembree, 1992) of 487 studies on problem solving found a positive impact on students' problem solving performance resulted from instruction especially being trained in heuristical methods. Ben-Chaim et al. (1988) found that both genders benefited significantly from the training program on spatial visualisation (SV) skills. However, the instruction in their study did not eliminate sex differences in SV skills. I assume that the applied instruction in this study may not be effective in the same way for females and males, although there is no evidence to support my opinion from their article. Would gender specific instruction eliminate or minimise gender differences in mathematical skills and to what extent should gender specific instruction be given with respect to different types of mathematical problems? These issues remain to be investigated in the future.

In my reviews of published studies, I did not find much research concerned with how characteristics of classrooms and teachers contributed to gender differences in strategy use during mathematical problem solving. However, some studies indicated that these variables were related to gender differences in mathematical achievement (Petersen and Fennema, 1985). Another small piece of evidence was that first-grade girls did not benefit as much as did boys from their perceptions of teachers' beliefs and instruction to develop their strategy use for problem solving from the very beginning of their academic training (Carr et al., 1999). In order to develop effective teaching to facilitate students' mathematics learning, these issues also need to be

[4] "Challenge seekers" and "challenge avoiders" were defined by Meyer et al. (1997) in their study as two different students groups based on the level of self-perception and behaviours.

addressed in future research studies.

FACTORS THAT CONTIBUTE TO GENDER DIFFERENCES IN MATHEMATICAL PROBLEM SOLVING

Many factors were suggested by researchers to make a contribution to gender difference in mathematical problem solving. A main line of research has focused on the gender differences in problem solving abilities. In this area, spatial abilities were of major concern. Another line of research paid attentions to speed of problem solving, in which a Math-Retrieval hypothesis is still in hot argument among some scholars (see, Gallagher & Kaufman, 2005). This section reviews some related studies that have examined gender difference in these factors with relation to mathematical problem solving.

Cognitive Abilities

Since 1974 when three cognitive abilities (verbal, quantitative and visual-spatial abilities) were identified by Maccoby and Jacklin (1974) as the loci of sex differences, numerous studies have been intrigued to confirm and extend their conclusions as a result. One line of research focused on the relationship between these cognitive abilities and gender differences in mathematical problem solving. However, evidence from these studies is inconsistent and sometimes conflicting. Examples of these inconsistencies are shown in the following discussion.

Spatial abilities

“Spatial abilities generally refer to skill in representing, transforming, generating and recalling symbolic, nonlinguistic information” (Linn and Petersen, 1985, p.1482). “Spatial skills involve the ability to think and reason using mental pictures rather than words” (Nuttall, Casey, and Pezaris, 2005, p.122). They are believed as one important component of mathematical thought during mathematical problem solving (Battista, 1990; Casey, 2003; Halpern, 2000).

There are a variety of spatial tasks, for example the Piaget Water-Level Task, Money’s Road Map Test, paper folding, hiding pictures, mental rotation tasks and so on, that are designed to examine spatial abilities. However, not all these tasks are related to mathematical processes. For example, only tasks involving spatial reasoning, which is composed of two types of spatial skills: visualisation (multistep reasoning) and orientation (mental rotation), were identified by Friedman (1995) to “have the most in common with mathematical processes” (p.23). I choose this classification to consider the gender differences in these spatial skills and their relationships with mathematical problem solving.

Spatial visualisation has been defined as “those spatial tasks which involve complicated multi-step manipulations of spatially presented information” (Linn and Petersen, 1985, p. 1484). Although many researchers have found that spatial visualisation and problem-solving were related (for example, Battista, 1990; Fennema and Tartre, 1985; Sherman, 1979), studies investigating gender differences in spatial visualisation have reported inconsistent results. Ben-Chaim et al. (1988) found that there were statistically significant gender differences in spatial visualisation among middle school students; while other researchers concluded that gender differences in spatial visualisation were small or null among middle school students (Armstrong, 1980; Fennema and Sherman, 1977, 1978; Linn and Petersen, 1985; Tartre and Fennema, 1995; Voyer et al, 1995). These inconsistent results may be due to the changes over time affecting the experiential influence on the measures, or due to different size of samples, or due to the instrumentation used (Ben-Chaim et al., 1988), or due to the test *per se* because some spatial tasks do not show gender difference (Halpern, 2000), or due to the influence of other variables such as different strategies used by males and females (Burin, Delgado and Prieto, 2000). Since observed patterns of mathematical problems solving for each gender may depend on the measure used in studies, this factor may need to be carefully examined.

Mental rotation refers to the ability to transform mentally and manipulate images when the object is rotated in three-dimensional space (Nuttall et al., 2005). Many studies suggested that there was a large gender difference in mental rotation ability with males outperforming females (Casey et al., 1995; Halpern, 2000; Linn and Petersen, 1985; Masters and Sanders, 1993; Voyer, et al., 1995). For example, Linn and Petersen’s (1985) meta-analysis found large heterogeneous differences in metal rotation. For example, Casey et al. (1995) found a significant relationship between mental rotation skills and the SAT-M scores in their female sample and this relationship remained after verbal tests scores were statistically controlled. They concluded that mental rotation ability was important for girls’ performance on the SAT-M. Casey et al. also suggested that for college-bound and high ability students mental rotation ability was a critical factor contributing to gender differences on SAT-M. However, this conclusion, drawn from a highly-selected sample of high ability students, is hard to disentangle the real situation of general student population.

Spatial abilities were reported to have relationship with mathematics test scores (Burnett, Lane, and Dratt, 1979; Casey, Nuttall, Pezaris and Benbow, 1995; Casey, Nuttall and Pezaris, 1997; Geary, Saults, Liu, and Hoard, 2000; Robinson, Abbott, Berninger and Busse, 1996; in Nuttall et al, 2005). This relationship indicates that gender differences in spatial abilities may contribute to gender differences in mathematical problem solving. However, they are many issues involved. Lohman (1979, 1988, 1996) concluded that variation in measures of general intelligence could explain a considerable proportion of performance on spatial tests, especially complex spatial tests. Linn and Hyde (1989) stated that their meta-analysis found no evidence to support the hypothesis that gender differences in spatial abilities contribute to gender differences in mathematics performance. Instead, they suggested that gender differences in spatial abilities were declining and that “gender differences occur on spatial processes are not obviously related to mathematics” (p.18). Chipman (2005) also pointed out that for those studies (for example, Fennema and Sherman, 1977, 1978; Smith, 1964; Stallings, 1985; Werdelin, 1961, in Chipman, 2005) that reported correlations between spatial abilities and mathematics performance, “the evidence for a specific contribution of spatial ability to mathematics performance… is surprisingly weak” (p.8). These disagreements show that gender differences in spatial abilities may not be an explanation for gender differences in mathematical problems solving and conclusions from related studies need to be critically re-examined.

Verbal abilities

The contribution of verbal skills to mathematical problem solving is evident. Many mathematics problems can be solved either by a spatial solution, or using a verbal approach (Fennema and Tartre, 1985; Casey, 2003). Verbal-logical abilities are regarded as being important to geometric problem solving for both genders (Battista, 1990). Evidence from a variety of sources has shown that there were gender differences in verbal skills with females outperforming males on many verbal tasks (Maccoby and Jacklin, 1974; Halpern, 2000). However, Hyde and Linn (1988) concluded that gender differences in verbal abilities had declined and were negligible now.

Quantitative abilities or mathematical abilities

Although there is no widely accepted definition of mathematical abilities (Byrnes and Takahira, 1993), there is common agreement that quantitative abilities are important to mathematical problem solving. Studies that reported gender differences in mathematical abilities favouring males had generally consistent conclusions. Maccoby and Jacklin (1974) suggested that “boys excel in mathematical ability” (p. 352) but few gender differences emerged until about ages 12-13 years, when boys' “mathematical skills increase faster than girls” (p. 352). Linn and Hyde (1989) concluded that “average quantitative gender differences have declined to essentially zero… females are superior at computation at all ages and that differences favoring males on problem-solving emerge in high school.”(p.19). Hyde et al. (1990) concluded that there were no gender differences on computation tasks but differences favouring males emerged on problem-solving tests in high school and college. They also reported that the more complex the task was, the greater the likelihood that better performance would be found in males. But Benbow and Stanley (1980) drew different conclusions. They indicated that gender difference in mathematical reasoning ability in favour of boys was observed before girls and boys started to differ in mathematics courses taking. This gender difference even increased through the high school years. Benbow and Stanley (1983) also suggested that males dominated the highest end on mathematical reasoning ability before they entered adolescence. The different findings of Benbow and Stanley might be due to their highly-selected samples: intellectually gifted junior high school students (primarily Grade 7 students). But there is no evidence to support that their conclusion can be generalised to a general population. In addition, although a large gender difference in quantitative abilities was found among gifted boys and girls (Halpern, 2000), actual gender differences favouring females were found in samples of general population (Hyde et al., 1990).

Speed of Processing Mathematical Information

In some literature, the ability to solve problems quickly in unfamiliar circumstances was regarded as crucial to mathematics performance on standardised tests such as the SAT-M (Gallagher et al., 2000).

Royer et al. (1999) suggested that speed of fact retrieval in the field of mathematics contributed to gender differences in mathematical problem solving on timed tests such as SAT-M. Their studies showed that males were generally faster than females on math-fact retrieval tasks while there were no gender differences on simple retrieval tasks. However, females were slightly faster than males on verbal processing tasks. It was hypothesised that the automatic execution of math-fact retrieval, resulted in additional working memory capacity that could be used for problem representation and solution planning during problem solving; and males were more likely than females to develop the ability to retrieve basic mathematical facts rapidly and automatically. Therefore males had higher mathematics performance on timed tests such as SAT-M (Royer et al., 1999). Similarly, Geary et al. (2000) indicated a stronger relationship between mathematical problem solving and math-fact retrieval than the relationship between mathematical problem solving and cognitive abilities; males tended to outperform females on math-fact retrieval tests and SAT-M. However, the sources of gender differences in math-fact retrieval have not been examined in their studies. In addition, response latency, which Royer et al. (1999) used as one measure of gender differences in math-fact retrieval, was found in their report actually to favour females (Wigfield and Byrnes, 1999).

Another hypothesis supposed that females, on average, had different response styles with males on timed tests on which females might take a slower and more cautious approach to answering problems (Goldstein, Haldane and Mitchell, 1990). Therefore, if females do not have enough time to complete test, they cannot solve as many problem as males do, their test cores may be significantly lower than males', even if there are no real differences in cognitive abilities between genders. Goldstein et al. hypothesised that if females were given more time to finish tests, gender difference would be eliminated. Their finding that there was no gender difference on untimed mental rotation test strongly supported their hypothesis. But several researchers did not agree with the opinion that speed of responding could contribute to gender differences in mathematical problem solving (Delgado and Prieto, 1996; Masters, 1998; Resnick, 1993; in Halpern, 2000). For example, Resnick (1993) found that gender difference did not minimise in modified versions of mental rotation tests that allowed more time. The contribution of gender differences in response styles to mathematical problem solving needs further examination.

More Complex Variables Related with Gender Differences in Mathematical Problem Solving

Although gender differences in factors discussed above can partly account for gender difference in mathematical problem solving, there are many questions that have not been answered. Are these gender differences more than individual differences? Are these differences correlated with biological, psychological and environmental variables? If both answers are yes, what kind of variables are they? Studies focusing on these questions are unsystematic. Therefore this section collects some possible explanations and classifies them into biological, psychological and environmental perspectives.

Biological Correlations

Sex differences in brain lateralisation function

An explanation in terms of sex differences in brain lateralisation function emphasises the different brain organisations of females and males and considers their relationships with gender differences in spatial and verbal abilities. It is assumed that the left and right hemispheres of females are more symmetrically (bilateral) organised for speech and spatial functions and males' are more asymmetrically (lateralised) organised. It also hypothesises that "greater lateralisation of function may be essential for high spatial performance and less lateralisation more important for verbal performance so males should superior in spatial tasks and females in verbal tasks." (Battista, 1990, p.48).

Springer and Deutsch (1981) reported that "both language abilities and spatial abilities are represented more bilaterally in females than in males" (P. 123). They suggested that "sex differences in verbal and spatial abilities may be related to differences in the way that those functions are distributed between the cerebral hemispheres in males and females" (p.121). Rilea, Roskos-Ewoldsen, and Boles (2004) found that the hemispheric processing varied across different types of spatial tasks. They suggested that spatial ability was not a unitary construct and different hemispheric processing might account for gender differences in these spatial measures. This study did not assess the strategies that people used to complete the spatial tasks, and whether strategies use correlated with hemisphere performance or not.

But Kimura (2002) stated an opposite point that for functions such as basic speech and spatial ability, there were no major gender differences in hemispheric asymmetry. Her laboratory work also found that damage to the right hemisphere had no greater effect on men than on women.

Sex differences in brain structure

This explanation suggests that the larger size of the corpus callosum (CC) in woman was correlated with a possible lower degree of lateralisation for spatial abilities (in Kimura, 2002; Halpern, 2000). This suggestion may be based on an assumption that larger CC, which is a major neural system connecting the two hemispheres, may permit better communication between hemispheres.

Influences of sex hormones

A line of research tended to attribute gender differences in cognitive abilities to the influence of sex hormones. For example, Geschwind's theory of prenatal hormonal effects (in Halpern, 2000; Halpern, Wai and Saw, 2005) assumed that higher levels of prenatal testosterone[5] in males would result in a greater level of right-brain dominance, with which males would develop cognitive ability patterns that were more closely associated with right hemisphere functioning. Therefore because both mathematical reasoning and spatial abilities were under greater control by the right hemisphere, males outperformed females on mathematical reasoning and spatial tasks. Another example was Nyborg's theory of optimal level of estradiol[6] (in Halpern, 2000; Halpern, et al., 2005). This theory suggested that sex hormone levels could partly account for gender differences in visual-spatial abilities. They suggested that males with high levels of estradiol (compared to

[5] Testosterone is a kind of male sex hormone.
[6] Estradiol is a type of estrogen, which is a kind of female sex hormone.

their male peers) and females with low levels of estradiol (compared to their female peers) would have higher level of spatial abilities. This theory needs strict confirmation from other studies.

Sex differences in brain activities during information processing

Some studies posited their theories on the basis of the sex differences in brain areas that are involved in mathematical information processing. Widely spread brain areas were reported to be involved in arithmetic processing, in which left frontal and parietal areas were described as the most common and important components (Burbaud, Camus, Guel, Boulac, Caillé and Allard, 1999; Cochon, Cohen, Moortele and Dehaene, 1999; Cowel, Egan, Code, Harasty and Watson, 2000; Dehaene, Spelke, Pinel, Stanescu and Tsvkin, 1999; Jahanshahi, Dirnberger, Fuller and Frith, 2000, in Rocha et al., 2004). Females consistently showed larger global field power for arithmetical processing in electroencephalogram (EEG) studies than males, and they also displayed different scalp field topography of enrolled brain areas during mental arithmetic (Skandries, Reik and Kunze, 1999). Rocha et al. (2004) found that the children's cerebral cognitive mappings (CCMs) were very different between boys and girls. Boys and girls exhibited "different neuronal assemblies" (p.369) for all types of arithmetic problem solving. They also suggested that this gender differences emerged at early elementary school stage and varied with age. According to their suggestions, the gender differences on response time might be explained by a better coordination between the sets of left frontal neurons and the sets of bilateral central-parietal cells in the case of male than in the case of females. However, only gender differences in brain activities of processing arithmetic problems were examined. This suggestion could not be applied to geometric or algebra problem solving due to lack of supporting data.

Psychological Contributions

Learning styles

Some researchers suggested that gender differences in mathematics can be explained by that boys and girls approached the learning of mathematics differently. Kimball (1989) offered a so-called "Rote versus Autonomous Learning Hypothesis" in her review of the gender and mathematics literature. It posited that females took a rote approach while males took an autonomous approach to learning mathematics. This gender differences in learning styles left females at a disadvantage when facing unfamiliar problems. Another hypothesis was advanced from Severiens and Ten Dam's (1994) meta-analysis of research after 1980. They concluded that males showed a greater preference than females to the abstract conceptualisation mode of learning.

Research has shown that males and females have different classroom experiences because they have different learning styles (Schwartz and Hanson, 1992). Females preferred to learn mathematics by using a conversational style, which fostered group consensus, encouraged collaboration, and contributed to constructing interrelationships of thoughts. Males, on the contrary, learned through argument and individual activity, which fostered independence and encouraged competition. But most classroom activities were organised to accommodate male learning styles (Ong, 1981); females were therefore more likely to be at a disadvantage than males in developing abilities or strategies for solving mathematical problems.

Learner's attitudes

This explanation accentuates that gender differences in learner's attitudes had an impact on how females and males solved mathematical problems. Many attitudinal differences, such as mathematics anxiety, confidence in mathematical ability, stereotype view of mathematics, perceptions of differential expectations and encouragement (Buchanan, 1987; Caplan and Caplan, 2005; Carr et al. 1999; Duff, Gunther and Walters, 1997; Fennema and Sherman, 1977; Tartre and Fennema, 1995), were found to contribute to gender difference in mathematics learning(Caplan and Caplan, 2005). One piece of evidence for this opinion was that the confidence gap between males and females might dissuade some females from taking shortcuts on tests such as the SAT-

M. Benbow (1988) stated that she was unable to find support for any of these explanations in data of the Study of Mathematically Precocious Youth (SMPY). But her opinion was not supported by much research (Royer et al., 1999).

Stereotype threat in mathematics tests

Stereotype threat[7] , the concern that others will view one stereotypically (Spencer, Steele, and Quinn, 1999), has been identified recently by some researchers to account for the gender differences in mathematical problem solving. Recent research (Keller, 2002; Spencer, Marx, Brown, and Steele, 1999; Shih, Pittinsky, and Ambady, 1999; Smith and White, 2002; Spencer, Steele and Quinn, 1999; Steele, 1999) has documented that stereotype threat interfered with girls' performance on standardised mathematics tests. For example, Walsh, Hickey and Duffy (1999) found that item content did not account for gender differences on the Canadian Test of Basic Skills (CTBS) and SAT, but gender differences were found when the female participants believed that these tests has shown gender differences before. Quinn and Spencer (2001) found that stereotype threat depressed female's performance on standardised mathematics tests. These findings suggested that the gender stereotype threat could be a key factor that accounted for gender differences in mathematical problem solving. Stereotype threat interfered with females' ability influenced their selection of problem-solving strategies. These studies will certainly undergo careful scrutinies and replications in different context with different groups. However, a new line of research may be sketched in the future investigation.

Environmental/Experience Influences

Socioeconomic variables

An explanation underlines socioeconomic variables played an important role in gender difference in children's development of spatial skills. These spatial skills may be acquired through playing with toys and materials that are related to spatial skills, while socioeconomic variables can affect children's opportunities to be engaged in such kinds of activities for promoting their development of spatial skills. However, these activities have been generally considered "more appropriate for boys by our culture" (Serbin, Zelkowitz, Doyle, Gold, and Wheaton, 1990, p.615). Therefore greater access to male sex-typed toys may be a factor in explaining for boys' better visual-spatial skills.

Serbin et al. (1990) concluded that mothers' occupation status had a significant impact on children's development of visual-spatial skills through greatly influencing the availability of playing with male sex-typed toys. Levine, Vasilyeva, Lourenco, Newcombe and Huttenlocher (2005) reported that socioeconomic status (SES) modified the gender differences in spatial skill. Boys in high and middle-SES groups outperformed girls on spatial tasks in these groups, while there was no gender difference in the low-SES group on spatial tasks.

Socialisation

Some researchers highlighted the important contribution of socialisation to gender differences in mathematics. In a longitudinal study to examine gender differences in mathematical problem solving skills among high ability students, Duff et al. (1997) posited an assumption that the interaction of attributes of mathematical problems with children's prior socialisation produced such differences. The 12-year-old participants (83 boys and 76 girls), who came from predominately white families, took part in two types of standardised mathematical problem-

[7] Steele (1997, 1998, in Halpern, 2000) found that when talented students took an advanced test of mathematics with a negative stereotype that male will outperform female, male students did score higher than female students. When these students took the same test with a positive stereotype that female and male will score equally, there was no overall gender difference was found in test scores. Steele called such a phenomenon as "stereotype threat". Steele (1999) also found that among the talented the fear of being associated with a negative stereotype impaired intellectual functioning and disrupted test performance regardless of preparation, ability, self-confidence, or motivation.

solving tests: the CTBS and the GAUSS[8]. The results showed that although males outnumbered females among high ability students on the CTBS, there was no gender difference on the GAUSS and no overall gender differences at all tests among the same students. They also reported that the less a student saw mathematics as a male domain, the better the student's performance on problem solving. Based on these findings, they argued that gender differences in brain structure could not account for gender difference in problem solving.

Differential in mathematics course taking

Some studies have attributed gender differences in quantitative SAT performance to males and females' differential patterns of course taking. They suggested that increasing female's high-level mathematical course-taking would effectively increase their performance in quantitative SAT.

> Students taking higher level mathematics courses would benefit from training in abstract reasoning and problem solving, from computational practice, and from generally being more comfortable in working with numbers. (Pallas and Alexander, 1983, p.170-171)

This explanation was in conflict with the conclusion of Benbow and Stanley (1980), who found that gender difference in mathematical reasoning ability in favour of boys, was observed among gifted youth before they started to differ in mathematics courses taking. The inconsistent conclusion might be due to the different samples they used.

Comprehensive Influences of All Affective Variables

The research discussed above illustrated that the situation of gender differences in mathematical problem solving is indeed complex. Many factors contribute to gender differences in mathematical problem solving, but the contributions of some factors are still being argued and only applicable in some specific areas, and they cannot account for findings from other areas. For example, Benbow (1988) reported that males outnumbered females at the upper end of the distribution in mathematically talented students. Benbow argued that these differences could not be explained by socialisation theories. However, this argument was in conflict with Duff et al.'s (1997) conclusion that socialisation was the main force behind these gender differences among high ability students. As Deff et al. indicated, genetic determinants could not explain why the same samples showed gender differences on one test but not on another test in the same study.

Another example is that the introduction of new neuronal techniques into educational areas, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET) and biochemical and genetic analysis, does not show much strong evidence for explaining how these factors produce gender differences in mathematics, although they provide more information for various problem-solving activities at a neuronal level. Caplan and Caplan (2005) argued that biological determinists did not present more convincing evidence than before was not because of a lack of advanced methodologies but because "…both many 19th-centrury researches[9] and many present-day researchers …are trying to explain a difference (in mathematics ability) that has not been solidly shown through behavioural measures to exist" (p. 30).

[8] The CTBS, was "a widely used standardized test of English and mathematical performance for Canadian students. Students were tested on the mathematical problem solving and concepts subscales at the beginning of the school year. The problem-solving scale in the CTBS is entirely composed of mathematical word problems". The GAUSS was "a test of non-routine mathematical problem solving in a multiple-choice format. It included computational problems as well as word problems. Some of the word problems involve geometry." (Duff, Gunther, & Walters, 1997)

[9] Caplan and Caplan (2005) argued that the 19-century researchers who sought desperately to find a basis in the brain for what they assumed to be men's superior intelligence tried to find some bit throughout the brain on which they could pin this assumption that men were superior in intelligence. For example, they assumed that men's brains were probably bigger than women's. However, it failed to consider the proportional of brain size to overall body size.

Gender differences in mathematics must be understood in a framework that considers a comprehensive influence from the interaction of all biological, psychological and environmental variables. Halpern (2000) developed a psychobiosocial model to understand the comprehensive influence from the interaction of all affective variables. This model emphasised the interaction and interdependent relationships among all variables and did not try to separate effects and their relationships into independent variables. By borrowing this model, we can obtain a general impression of how biological and psychological variables interact with both experience and the environment to contribute to gender differences in mathematical problem solving patterns.

DISCUSSION AND CONCLUSIONS

Gender differences in mathematical problem solving, that is believed to be an important factor that contributes to gender differences in mathematics performance, have been given increased attention by researchers in the last few decades. I have presented here some of the findings from relevant studies that examined this issue. A review of these studies reveals that the situation of gender differences in mathematical problem solving is very complex.

The literature has consistently reported that males perform better on mathematics problem solving than females do among high ability students on standardised mathematics tests. These gender differences are generally obvious in high school and in college and vary across mathematical tasks. However, females and males' different patterns of mathematical problem solving, as reflected by different strategy use in problem solving, can be traced back to the very early stage of elementary schooling. It is found that students' strategy use is related to cognitive abilities, interfered with psychological characteristics and mediated by experience and education. In order to interpret these patterns, factors involved in mathematical problem solving are taken into this discussion, including cognitive abilities, speed of processing information and many complex variables related problem solving such as physiological differences in brains, influences of sex hormones, learning styles, learners' attitudes, stereotype threat in mathematics tests, differences in socialisation, and the impact of socioeconomic variables. All these factors are reported to contribute to mathematical problem solving, but the contributions of some factors are still in doubt and they are only be applicable in some specific areas.

A complex issue is raised from investigating gender differences in factors contributing to mathematical problem solving. How do these biological, psychological and environmental variables interact with each other and form a comprehensive influence on students' development of problem solving abilities and strategies? How do females and males develop different patterns of solving mathematical problems? There is not much related research. I suggest that the comprehensive influence of all affective variables should be understood in a complex and interactive framework. Halpern's (2000) psychobiosocial model may be employed to understand this issue, but our understanding needs to continue to develop and be based on the findings of future investigations.

Meanwhile, the fact that gender differences in mathematical problem solving are not biologically determined while possibly influenced by the combined impact of many different factors that have biological, psychological and environmental origins, give us promise that education can play a great role in eliminating or reducing gender differences in mathematical problem solving. On one hand educators need think about how to help all female and male students develop problem-solving abilities by using appropriate instruction. On the other hand educators need to consider critically the positive and negative impacts of classroom variables and make conscious effort to promote gender equity in mathematics learning.

From the studies reviewed taken together, several issues are worthy of attention:

First, the SAT-M is designed for able students in high school and to be predicators of academic performance in college. The SAT-M scores are not necessarily a measure of cognitive abilities and not the only measure of performance on mathematical problem solving. Studies need to focus more on what people can do on problem tasks in practical situation and less on how well they can take tests.

Second, many standardised mathematics tests including the SAT-M are multiple choice tests, thus they do not provide diagnostic information about students' strategy use and working procedures during problem solving, the test scores may not reflect the real differences in problem solving between boys and girls on problem tasks in practical situation.

Third, findings from pre-selected samples can not be generalised to a general population. There is no meaning in repeatedly confirming gender differences among these highly selected samples. In order to investigate differences in mathematical problem solving patterns it may be more helpful for researchers to focus on individual differences, rather than to assume that girls are a inferior group while boys are a superior group or *vice versa*.

Forth, there is no single theory that can explain all the findings from different perspectives. Any conclusion that attributes gender differences in mathematical problem solving to a single factor is clearly problematic.

Fifth, little research has specified why gender differences in problem solving change over time and why females and males have different preferences for strategy use with respect to different types of mathematical problems.

Sixth, research on how different factors interact with each other to form the pattern of mathematical problem solving between genders is still very scant.

Consideration of these points can be helpful when designing future investigations.

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