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REVIEW ARTICLE

Gender Differences in Science: An Expertise Perspective

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Abstract The purpose of this paper is to propose a new approach to research on gender differences in science that uses the work on expertise in science as a framework for understanding gender differences. Because gender differences in achievement and participation in the sciences are largest in physics, the focus of this review is on physics. The nature of expertise is first discussed and a framework that focuses on factors that influence the emergence of expertise in physics is presented. This is used to interpret what is known about gender differences in science, particularly physics. Next, the potential contributions of the research on gender differences to our understanding of expertise are discussed. Using what is learned from these two areas of research, recommendations are made for future research examining gender differences in physics. It is suggested that such an approach be used for other areas of science, such as chemistry, where large gender differences in achievement and participation also exist.

Keywords Physics · Gender · Expertise · Science

Gender Differences in Science

The underrepresentation of women in the sciences is a significant and well documented societal concern (Miller *et al.* 2006; Stake 2006). Although the reasons for the problem are debated, there is no debate about the fact that women are underrepresented in the scientific community. For instance, in recent years, women received 34% of the master's degrees in computer science, 21% of the master's degrees in physics, 41% of the Masters degrees in chemistry, and 21% of the master's degrees in engineering (National Science Foundation

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[NSF] 2004). Results for doctoral degrees were similar: Women received 19% of the doctoral degrees in computer science, 13% of the doctoral degrees in physics, 32% of the doctoral degrees in chemistry, and 17% of the doctoral degrees in engineering. Thus women are greatly underrepresented in the sciences, particularly in more advanced degrees and degrees involving physics and engineering.

Gender differences in science achievement on standardized tests from K-12 (e.g. National Assessment of Educational Progress [NAEP] 2005) have been thought to keep females from pursuing advanced courses and careers in science (e.g. Katz *et al.* 2006). When standardized test scores are examined, gender differences in achievement have been reported as early as the fourth grade, and the gap in achievement increases as students progress through school; these gender differences exist on both the life science and physical science sections of achievement tests including the NAEP and the International Assessment of Educational Progress (Beller and Gafni 1996; NAEP 2005). The largest differences in achievement, however, exist in the physical sciences, particularly in physics (Beller and Gafni 1996; NSF 2004). From elementary school through high school, males have been found to have higher scores on physics sections of achievement tests (e.g. NAEP 2005).

In K-12, a different pattern of gender differences is observed for grades assigned by teachers. Gender differences in course grades in favor of males emerge only in college, and the evidence for that is not consistent. In elementary and middle school, males receive lower grades than females in all subjects, including science (Kleinfeld 1998; Posnick-Goodwin 2005). In high school (Willingham and Johnson 1997), males and females receive similar grades in their science courses, including physics courses. The research examining science Grade Point Average (GPA) in college is inconsistent, with some research suggesting that female undergraduate students perform as well as males in science courses (Adelman 1991; Glynn *et al.* 2007), and other research suggesting that male students outperform females in science courses, particularly in physics and engineering courses (e.g. Taasoobshirazi and Carr, unpublished manuscript; Felder *et al.* 1995). These results held for both science majors and non-science majors.

There is substantial research indicating that males outperform females in introductory-level physics courses required for physics and engineering majors (e.g. Taasoobshirazi and Carr, unpublished manuscript; Tai and Sadler 2001). This gender difference may explain the higher percentage of women, in comparison to men, switching from a physics major to a nonscience major (Larose *et al.* 2006; Seymour and Hewitt, 1997; Stumpf and Stanley 1996). However, more women than men leave physics, even when controlling for factors such as such as first-year grades (Seymour and Hewitt 1997). “Switchers” from physics and engineering majors to nonscience majors (which are primarily female) and “nonswitchers” have often been found to be similar in their self-reported GPA and the amount of time they worked in their science courses (Seymour 1992a, 1992b; Xie and Shauman 2003). This suggests that even when women are interested in pursuing physics as evidenced by their initial entry into these college programs, and are achieving in physics, other factors may influence whether they will stay in the program.

It is unclear why females are able to attain similar grades as males in the classroom from elementary through high school, but not on science achievement tests administered during these years. It is also unclear why females receive lower grades than males in college-level science classrooms. It has been suggested that females receive higher grades in class because they are more concerned with pleasing the teacher (DeBacker and Nelson 2000) and have fewer disciplinary problems in the classroom (Posnick-Goodwin 2005). These explanations are feasible if teachers interpret females’ compliance as evidence of achievement. Classroom grades, therefore, may measure good behavior in addition to actual skill and knowledge. It is unlikely that achievement tests do the same. It is also unlikely that good behavior plays a role in classroom grades in college. No research, however, has examined these hypotheses.

Researchers have identified a number of possible explanations for why females perform more poorly than males in science, and in physics in particular, including differences in teacher support, parental support, motivation, enrollment patterns, and hands-on experience (e.g. Desouza and Czemiak 2002; Enman and Lupart 2000; Greene and DeBacker 2004; Mattern and Schau 2002; She 2001; Shin and McGee 2002; Tenenbaum and Leaper 2003). Although this research has provided insight into the variables that may influence gender differences in science, it lacks a theoretical framework. We propose the use of an expertise framework to interpret the research on gender differences in science. We believe that the expert-novice paradigm can provide a firm theoretical framework for conducting research that may help explain the well-documented gender differences in science. Because gender differences in achievement and participation are largest in physics, the focus on this particular review is on physics. However, we suggest that similar research be conducted in other areas of science, such as chemistry, where large gender differences in achievement and participation also exist.

What is Expertise?

Expertise is most often described as a collection of characteristics that discriminate experts and novices. Within their domain of practice, experts use more goal directed strategies for solving problems, have greater knowledge, more organized knowledge, greater motivation, engage in more deliberate practice, tend to receive more social support, and are better monitors of their performance (Alexander 2003; Bloom 1985; Bruning *et al.* 2004; Ericsson 1996; Hatano and Oura 2003). Although these are characteristic of experts in any domain, additional domain specific characteristics exist (e.g. Heyworth 1999; McIver 2000; Schmidt and Boshuizen 1993). For example, the use of pictorial representations differentiates novices from experts in physics, but not in biology (Boster and Johnson 1989). In medicine, the development of expertise is linked to the formation of narrative structures called illness scripts that are used to diagnose new cases (Schmidt and Boshuizen 1993). In computer science, important characteristics of expertise include the ability to deal with unexpected output, favor power over simplicity in programming, and be flexible with use of programming syntax (McIver 2000). While there may be a number of characteristics typical of all experts, some characteristics of experts are tied to particular domains.

Research examining expertise suggests that it takes approximately 5 to 10 years to develop expertise in a domain (Bruning *et al.* 2004; Ericsson 1996). Novices are typically defined as those who have only “rudimentary competence in the domain” (Priest and Lindsay 1992, p. 399) whereas experts are defined as individuals with advanced degrees and years of practice within their domain of expertise (Dee-Lucas and Larkin 1986). In regard to physics, novices are typically found in the literature to be high school or introductory-level college physics students (Dee-Lucas and Larkin 1986; Finegold and Mass, 1985), whereas experts are typically found to be physicists, physics professors, or doctoral physics students (Chi *et al.* 1981; Larkin 1983).

Expertise is an outcome of the experience and personality. Research by Ericsson, Krampe and Tesch-Romer (1993) gives us insight into the processes that support the development of expertise. From this work we know that people who achieve the highest levels of expertise possess the motivation to move to higher levels of achievement through deliberate practice. Work within the field of gifted education (Abuhamdeh and Csikszentamihalyi 2004; Bloom 1985) has examined social and personal contexts that influence the emergence of expertise. This work shows us that families and societies can support or suppress the emergence of expertise.

Unfortunately, within the domain of physics and most sciences, expertise tends to be defined as differences in problem solving skills and knowledge. There is little recognition of the larger context in which physics expertise emerges. We must consider problem solving skills and knowledge, but we must also understand how this knowledge and skill develops within a larger social and personal context. The research on gender differences in science suggests that it is these social and personal contexts that may be of great importance. The gender differences literature, however, has tended to ignore possible differences in problem solving skills and knowledge which must also be considered.

Gender Differences from an Expertise Framework

The expertise framework used here emerges out of the research on expertise in general and the research on expertise in physics. If we are to discuss expertise in physics we must examine variables that have been identified as being important, including problem solving strategies, pictorial representation, problem categorization as a measure of depth, breadth, and organization of conceptual knowledge, and metacognitive skills (e.g. Anzai 1991; Chi *et al.* 1989; Davis 1989; Larkin *et al.* 1980). Our expertise framework differs from the traditional approach in the physics expertise literature in that it also includes characteristics of expertise not typically identified including the importance of social support, motivation, and deliberate practice.

Several problems arise in interpreting the research on gender differences in physics using an expertise framework. First, the bulk of the research on expertise in physics focuses on novice–expert differences in strategy use, pictorial representation, conceptual knowledge, and metacognition. There is little research in the gender differences literature examining these variables. What has been done has involved broad assessments, such as standardized achievement tests that do not get at the specific skills assessed by the expertise research.

Second, although there is a large body of research examining experts and novices in physics, none of the studies address gender differences within and across expertise categories. The number of males and females categorized as experts or novices in these studies is typically not mentioned. Examining gender differences in the variables that may account for gender differences in physics would help explain why females tend not to achieve in and pursue physics.

Our review is also limited by a lack of research examining how physics experts function in the real world (Ericsson 2006a, b; Reif and Allen 1992). The existing research, for instance, provides little explanation of experts' ability to consistently perform at a high level in authentic settings. By focusing on differences in basic problem solving skills, this research has missed key characteristics that are important in distinguishing experts from novices (Tuminaro and Redish 2007).

Despite these problems, we believe that approaching the problem of gender differences from the expertise perspective is important. Presented below is an in-depth review of all of the classic and current research on expertise in and outside of physics using the framework presented above. The research on expertise in physics is used to interpret what we know about gender differences in science, particularly in physics. In turn, an in-depth review of the existing research on gender differences in science, particularly physics, is used to inform the research on expertise.

Problem solving strategies

Experts and novices use qualitatively different strategies that reflect differences in the quantity and nature of conceptual knowledge (e.g. Larkin 1985). Novices' strategies are more data driven in that they do not have the knowledge that allows them to set up and carry out a solution from start to finish. Instead, they must start from givens and work towards a hoped for solution. Experts, in contrast, have a good understanding of the complete problem solving process. This allows them to be more efficient in their problem solving.

Within the domain of physics, novices tend to use the working backward strategy. Novices start by forming an equation that contains the goal of the problem (Larkin 1985). If the equation contains additional unknown variables that are not provided in the statement of the problem, the novice creates additional equations, aiming to solve for those unknown variables. This process is repeated until all variables are known or can be solved. The process is data driven with a goal of performing calculations to solve equations to find unknowns. Experts, in contrast, tend to use the working forward strategy (Larkin 1985). When solving physics problems, experts work forward from a set of equations generated from the information provided in the problem, concluding the solution sequence with the goal of the problem. This process is based on the understanding of physics principles and laws that lead to meaningful calculations. While the working forward and working backward strategies may result in the same answer, the working forward strategy is considered to be purposeful problem solving, while the working backward strategy involves manipulating equations with almost no planning and little conceptual understanding of what is being done (Larkin 1985). However, without having an understanding of the equations being used and the direction the problem solver is going, a novice is likely to find him or herself unable to solve the problem.

Although the working forward strategy is a characteristic of experts, the research indicates that novices can use this strategy. Larkin *et al.* (1980a) asked eight novices, who were first year college physics students, and eleven experts, who were either physics professors or graduate students in the physics department, to solve mechanics problems and think-aloud as they solved the problems. They found that the experts primarily used the working forward strategy while the novices primarily used the working backward strategy. Priest and Lindsay (1992) compared 74 novices (non physics majors) to 30 physics experts (doctoral physics students) and found that the experts used the working forward strategy to a greater extent than the novices. When students receive extensive instruction on how to conceptually analyze problems before solving them, their strategy use reflects that of experts. For instance, Zajchowski and Martin (1993) examined 10 introductory college physics students solving mechanics problems and thinking aloud as they solved the problems. They found that the more novice problem solvers (as assessed by a pretest), who had been instructed on how to conceptually analyze problems prior to solving them, were using the working forward strategy to the same extent as the more expert problem solvers.

The working forward strategy appears to be closely tied to a good conceptual understanding of the relevant material (e.g. Anzai 1991; Taasoobshirazi and Carr, unpublished manuscript; Schneider 1993). Specifically, it appears that the working forward strategy is used if the problem solver understands the concepts behind the problem, whereas the working backward strategy involves equation manipulation due to a lack of understanding of the problem and associated concepts. Thus, the working forward strategy is characteristic of experts because of their more expert understanding of physics. When experts encounter a very complicated problem related to difficult material, they often exhibit the use of the working backward strategy (Anzai 1991; Taasoobshirazi and Carr, unpublished manuscript). In contrast, giving a very easy problem to a novice will evoke the working forward strategy (Taasoobshirazi and Carr, unpublished manuscript). This also indicates that the forward/backward distinction is tied to the difficulty level of the problem for the individual solving it rather than a stable characteristic of experts and novices. Novices (students) are more likely to encounter problems that they find difficult than experts (teachers), especially in introductory physics courses. Ensuring novices understand the material and concepts underlying physics problems before attempting to solve the problems appears to be a way to increase the use of the working forward strategy (Zajchowski and Martin 1993). However, it is unlikely that encouraging participants to use the working forward strategy without assisting them in understanding the concepts behind the problems will be sufficient in improving their strategy use.

No research examines gender differences in the working forward and working backward strategies in physics. In looking at the domain of science more broadly, gender differences have been hypothesized to be due to females' use of rote strategies (Ridley and Novak 1983). The few studies that have examined gender differences in students' strategy use focus on students' learning strategies rather than problem solving strategies, and examine whether students are focusing on the conceptual aspects of the material when learning science or on the rote memorization of facts. Meece and Jones (1996) used self-reports to examine gender differences in fifth and sixth grade students' strategy use during lessons over six science topics including the human body, forces of energy, and space travel. They found little evidence for gender differences in students' use of conceptual and rote strategies. Nolen (1988) also used a self-report to determine gender differences in eighth grade students' strategy use in science in general, and found that females used more conceptual and fewer rote strategies than males. Atkin (1977) examined college students' strategy use in college-level organic chemistry and found no gender differences for rote memorization, but reported that males were more likely than females to use conceptual strategies. The results for middle school students indicate that females may be using more expert strategies than males or that there are no gender differences that exist. The one study examining actual strategy use in an older population indicates gender differences in favor of males' use of more expert strategies.

There are a number of critical problems with these studies. Two of the studies used self-reports to examine differences in students' strategy use, and in these studies, students' actual strategy use was not documented as is typically done in research on expertise. There may be problems with the validity of the reports if the students were unable or unwilling to respond accurately. For instance, females have been found to be more concerned than males with pleasing the teacher (DeBacker and Nelson 2000), and may respond in such a way as to look good to the teacher or researcher. For this reason, it is necessary to go beyond self-reports, and observe students' completed work and engagement in relevant activities in order to get a more accurate picture of students' strategies. Of the studies that used self-reports to determine strategy use, one of the studies examined students' strategy use, but not strategies linked to performance within a specific domain of science, likely making it difficult for the students to respond accurately. None of the studies examined students' strategy use in a specific subject domain using the research on expertise as a guide for understanding the strategies being used.

Differences in strategic approaches to problem solving may explain the discrepancy between course grades and standardized achievement tests. Much of science instruction and assessment in elementary, middle, and high school classrooms involves the memorization of scientific terms and facts (Dietel *et al.* 1991). Females tend to describe learning science as facts to memorize (Kahle and Lakes 1983), suggesting that they may use rote memorization to learn science. This may explain why females are able to perform as well as or even better than males in science classes at these grade levels. The use of memorization, however, is less likely to be useful on achievement tests or in college level science courses. For instance, for physics, rote memorization is negatively related to college classroom achievement (Cavallo *et al.* 2004), and would likely lead to the use of the working backward strategy. If males are using more conceptual strategies, this would still allow them to succeed in the classroom from K-12, but also on achievement tests and in college level science courses.

Problem representation

The ability to pictorially depict key variables and their relationships in physics problems is a major difference between expert and novice problem solvers. Before solving a problem, experts will represent the relationships in the problem by sketching a picture of the problem. Novices, in contrast, focus solely on representing the problem as a set of equations (e.g. Dhillon 1998; Larkin *et al.* 1980b). Pictorially representing a problem is important in physics because it allows the problem solver to determine which approach to the problem is appropriate, to identify the forces and energies at work, and to reduce the amount of information that must be attended to at one time (Larkin *et al.* 1980b; Larkin and Simon 1987). Further, a pictorial representation also allows the problem solver to visualize the role and interaction of the various factors in a problem. Pictorially representing problems before beginning to work on calculations is particularly important as problems become more complex and additional factors (e.g. angles, forces) begin to play a role in the problems. Van Heuvelen (1991) suggests that novices often fail to draw a sketch of the problems they are solving because they do not understand the concepts and principles involved in the problems. Thus, as novices progress towards expertise and gain more conceptual knowledge, the use of pictorial representations is likely to emerge.

Although there is no research suggesting that males are more likely than females to pictorially represent the problems they are solving, there is ample research indicating that males of all ages outperform females on tests of spatial ability, including three-dimensional, mental rotation, spatial perception, spatial visualization, and dynamic spatial ability tasks (e.g. Law *et al.* 1993; Linn and Petersen 1985). Gender differences in science achievement, including physics achievement, have been linked to gender differences in spatial ability (Benbow and Stanley 1984). For instance, Law *et al.* (1993) examined college physics students' spatial abilities and found that the males' spatial abilities were significantly better than that of females, and this was linked to higher achievement on a physics task.

Physics is taught in an abstract and mathematical way that involves the interpretation of visual and spatial relations (Larkin *et al.* 1980b). The male advantage in physics may be partly due to the spatial and visualization demands common to physics problems. When solving physics problems, pictorial representations may be used more by males than females because of their more expert spatial abilities, and these representations may be more complex and accurate when drawn by males.

Conceptual understanding and problem categorization

One factor that has a significant impact on expert performance is domain specific knowledge and the organization of that knowledge. Experts in all subject domains have greater domain knowledge, and this knowledge is better organized in comparison to that of novices (Chi *et al.* 1981; Reif and Heller 1982). In physics, evidence of the difference between experts and novices in their conceptual understanding and how they store, relate, and use this knowledge can be found in how they categorize problems (Chi *et al.* 1981), with experts focusing on the principles and laws underlying problems, and novices focusing on surface features of problems when making problem categorizations.

Studies of problem categorization indicate that expert problem solvers tend to view two problems as similar when the same law or principle can be applied to solve the problems. Novice problem solvers, in contrast, tend to view two problems as similar when the problems share the same surface features such as terminology or objects (Chi *et al.* 1981; Dufresne *et al.* 1992; Larkin *et al.* 1980a). For example, Chi *et al.* (1981) asked eight experts (doctoral physics students) and eight novices (undergraduate physics students who had just completed a semester of mechanics) to categorize 24 mechanics problems based on their similarities, and to think-aloud as they categorized the problems. They found that the novices tended to categorize the problems based on surface features, including the objects referred to in the problems (e.g. ladder, inclined plane) and the physics terms mentioned (e.g. friction, gravity). The experts tended to categorize the problems based on the major principles underlying the problems.

Although there is no research examining gender differences in students' problem categorizations, if females are using memorization to learn physics, their knowledge base may be poorly organized in a way that would result in categorizations based on superficial rather than deep features of problems. This would suggest a poor conceptual understanding of the physics material. The tendency to score lower than males on physics sections of achievement tests suggests that females have less conceptual knowledge, but we need to know more about the ways in which females differ in their understanding of physics and how these differences emerge.

Metacognition

Research indicates that effective metacognition is considered essential for efficient problem solving and for the transition from novice to expert (Tobias and Everson 2000). Because good problem solving depends on both the appropriate selection of a strategy as well as its correct execution, expert problem solvers can explain the strategies they are using, why they are using them, monitor the effectiveness of the strategy, and will select another strategy if the one they are using is not working. In contrast, novice problem solvers are often unable to explain and monitor their choice and use of strategies very well, and will continue to use a strategy even after it has failed to work (National Research Council [NRC] 2001).

Metacognition has been found to be so critical for problem solving that high levels of metacognition can compensate for low problem solving ability (Howard *et al.* 2000). For example, Swanson (1990) found when examining high school students' verbal responses to a questionnaire, that low-aptitude, highly metacognitive students outperformed high-aptitude, low metacognitive students in determining the number of steps needed to solve pendulum and fluid problems.

Metacognition is especially important with problems that require an understanding of the principles or laws. Shin *et al.* (2003) found that high school astronomy students who had good metacognitive skills were more likely to do well on problems that required a good conceptual understanding. In contrast, metacognition was not a strong predictor of performance on problems that could be solved through rote computation. These results suggest that metacognition is most important when students must use their conceptual knowledge to set up and solve problems.

Conceptual understanding has been found to improve when metacognitive skills are explicitly taught. Neto and Valente (1997) found that high school students who were instructed to reflect on their problem solving while solving mechanics problems were able to form a deeper conceptual understanding of the material in comparison to students not receiving metacognitive instruction. Koch (2001) taught introductory college physics students techniques to assess their comprehension while reading a physics text. She found that these students, compared to students who did not receive the instruction, received higher scores on a physics assessment.

Although metacognition has been found to be critical for successful problem solving and understanding, no research has examined differences in the metacognitive skills of males and females in science, or how metacognitive skills influence student problem categorizations, or the use of different strategies in physics or other areas of science. Good metacognitive skills are likely closely tied to the use of the working forward strategy and more expert problem categorizations, but its role on the use of this strategy and on categorizations has not yet been explored. Assuming that expertise emerges as a function of reflection on what one knows and what one needs to know, it is important to determine whether females' lower performance in physics is due to poor metacognition.

Teacher and parent support

No research examines the role of social support in influencing expertise in physics. However, using the general framework of expertise, social support is expected to be critical for the transition to expertise (Bloom 1985). Practice needed to acquire expertise in any domain is often overseen by parents and instructors who provide instruction, feedback, and emotional support. Bloom (1985) identified three key phases in the development of expertise in any domain. In each of these phases, social support is important. In the first few years of practice, there is a highly supportive home environment in which motivation and deliberate practice are stressed. During the middle years, the first signs of expertise are expected to emerge, and the student becomes increasingly dependent on skilled mentors. In the later years, as an individual becomes more expert, social support is obtained through a single master teacher alongside steady practice and feedback. Whereas we know almost nothing about the role of social support in the emergence of physics expertise, we know a considerable amount about how this process may be curtailed for females in relation to males. In the classroom and at home, males receive more attention, instruction, and feedback about science than do females; this is particularly true when it comes to physics (Tenenbaum and Leaper 2003).

In elementary, middle, and high school science classrooms, males receive more attention from teachers than do females (e.g. She 2001). For instance, in middle and high school science classrooms, males are called on more frequently to answer questions (Jones and Wheatley 1990), typically dominate almost every type of classroom interaction, and receive more academically related questions than do females (Lee *et al.* 1994).

Science teachers have been found to have lower expectations for females than males (Worrall and Tsarna 1987). As an example, Shepardson and Pizzini (1992) examined elementary school teachers' perceptions of the scientific ability of their students. They found that teachers perceived males to be stronger than females on cognitive intellectual skills, including the ability to analyze, synthesize, hypothesize, evaluate, interpret, and question. Females were perceived to be stronger than males on cognitive process skills, including the ability to measure, observe, communicate, graph, manipulate equipment and materials, and record findings. The perception that females are not as competent in the intellectual skills needed for advanced science may be subtly communicated to students, and may influence student–teacher interactions.

Gender differences in teacher beliefs and responsiveness exist even though females are more concerned than males with pleasing the teacher (DeBacker and Nelson 2000), and initiate as many teacher interactions as do males (Greenfield 1997). Teachers' additional support and attention towards males in K-12 may be to keep them on task (Posnick-Goodwin 2005), but it is unclear why teachers have lower evaluations of females, particularly since females tend to do well in the classroom in these years. The quality of student–teacher interactions need to be better examined to determine whether low teacher expectations for females is communicated to students and why it is that females perform as well as males in elementary, middle, and high school classrooms despite these low expectations.

Less research has examined gender differences in teacher support at the college level. In college-level physics and engineering classrooms, females have been found to receive less feedback and support from instructors than do males (Brainard and Carlin 1998). Other research, however, indicates that there are few, if any, differences in how male and female science undergraduates are perceived and treated by science faculty (e.g. Kardash 2000; Seymour and Hewitt 1997; Stentra *et al.* 1994). Rather, the problem appears to be that females need more support and guidance from instructors than do males, particularly in physics (Wee *et al.* 1993), and this support is unavailable in college level science courses (Mazur 1997). For females, more than males, feedback, attention, and support from instructors play a critical role in females' decision to participate in science; if females do not get the support they need, they become less likely to major in science (Hewitt and Seymour 1991; Tobias 1989). It is unclear whether this is the result of a lack of preparation or a need to have more personal contact with the professor. Regardless, the teacher-dominated, competitive, and impersonal environment commonly found in college science classrooms, particularly physics and engineering classrooms, is a problem for females (e.g. Hewitt and Seymour 1991; Mazur 1997; Siebert 2001; Tobias 1990).

In addition, females, more than males appear to be unhappy with science instruction at the college level (e.g. Kardash and Wallace 2001; Seymour 1995). Females find science classrooms to be cold and unfriendly environments (Mannis *et al.* 1989). Kardash and Wallace (2001) found that females were significantly less likely than males to feel that science professors emphasize the understanding of concepts as much as the acquisition of facts, explain science in a way that makes sense, are willing to review difficult information, and ensure that students understand the material. Thus it appears that females see science instruction at the college level as less supportive and informative than males. It is likely that these classroom factors play some role in the attrition of females in the sciences.

Similar problems occur in the home. Parents believe that science is less interesting and more difficult for their daughters than for their sons (Tenenbaum and Leaper 2003). This belief appears to influence the way parents interact with children when discussing science. Mothers of children between 5 and 9 years of age were found to use a higher proportion of science process talk with their sons than with their daughters (Tenenbaum *et al.* 2005). Furthermore, when discussing exhibits in science museums with their preschool and elementary school children, parents provided their sons with scientific explanations 29% of the time, and provided their daughters with scientific explanations only 9% of the time (Crowley *et al.* 2001). Tenenbaum and Leaper (2003) found that fathers were more likely to use scientific vocabulary with their pre-adolescent and adolescent sons than daughters across a variety of different science tasks, and that their use of scientific vocabulary was most gender-differentiated for physics tasks. These findings are critical because parental support is found to have significant effect on achievement which, in turn, is found to influence self-efficacy and outcome expectations (Ferry *et al.* 2000).

Less research has examined gender differences in parent support in science at the high school and college level. The research that exists indicates that high school and college females, more than males, rely on parent support and feedback (e.g. Hazari *et al.* 2007; Hewitt and Seymour 1991). For instance, Hewitt and Seymour (1991) found that the key reason that college level males decided to major in physics or engineering was because they enjoyed or excelled in these courses, while for females the key reason was due to encouragement from parents and teachers. Baker and Leary (2003) found that "the few instances in which the girls chose a physical science career were all based on having experienced that science with a loved one" (p. 189). In addition, the International Study of Women in Physics reported that the factor that women physicists cited as the most important to their success was the support of their parents, husbands, advisors, professors, and colleagues (Ivie *et al.* 2001). Parents tend to be sympathetic of high school and college females' choice to refrain from enrolling in advanced physics classes because they see physics as a predominantly male subject, and unimportant to the future career of their daughters (e.g. Solomon 1997). This is important because parents' belief that science is relevant and leads to a better career for their daughters plays a significant role in influencing their daughter's participation and achievement (Hazari *et al.* 2007; Hewitt and Seymour 1991).

Across all ages, female students are more influenced by both their teachers' and parents' perceptions, pay more attention than male students to advice given to them by teachers and parents (Hess *et al.* 1984), and appear to need more support from parents and teachers than do males (Hewitt and Seymour 1991; Wee *et al.* 1993). A lack of support and feedback may keep females from achieving and participating in science. Nevertheless, it has been found that after controlling for social support, gender differences still exist (Foote 1996), indicating that social support in the home and classroom does not entirely account for gender differences in performance and participation.

The research on gender differences helps inform the research on expertise in physics by showing how emerging expertise may be curtailed for females through a lack of social support. Females appear to be particularly susceptible to social influences and the research suggests that they receive little social support in science, particularly when it comes to physics. Expertise, therefore, may not develop in the same way for all students and some variables may be more important for subgroups of students.

Motivation

Although not described in the expertise research in physics, using the general framework of expertise, motivation is found to be critical for the transition to expertise (Ericsson 1996). Motivation to engage in activities that lead to expertise is vital (Ericsson *et al.* 1993), particularly when practice becomes tiring, frustrating, or boring. Ericsson (1996) describes the role of motivation in the process of deliberate practice. During deliberate practice, students set a goal, act on that goal, assess the outcome, and revise their behavior. This process requires a great deal of effort, which is unlikely to occur without significant motivation. Whereas we know almost nothing about the role of motivation in the emergence of physics expertise, we do know how this process may be curtailed for females. The research examining gender differences in motivation indicates that from middle school through college, females have less motivation to pursue science courses and careers, particularly when it comes to physics (Morgan *et al.* 2001).

While all students lose interest in science by the time they reach middle school (Jones *et al.* 1992), the drop is more drastic for females. In both middle and high school, females have less interest in science than do males (Lupart *et al.* 2004), particularly when it comes to physics (Beller and Gafni 1996), and feel less confident about their scientific abilities (She 2001). Similarly, in college, females have lower motivation than males to pursue science classes, majors, and careers, especially those pertaining to physics and engineering (e.g. Morgan *et al.* 2001). For college level physics and engineering students, low motivation results in poor achievement (Willson *et al.* 2000).

The tendency to view science as a masculine field may lower females' motivation to pursue science classes and careers. Students from elementary to high school have been found to perceive science as a masculine subject, and perceive scientists as predominantly male. Chambers (1983) administered the Draw a Scientist Test (DAST) and found that only 28 of the 4,807 students in kindergarten through fifth grade that were asked to draw a picture of a scientist drew a female scientist. All of these 28 drawings were drawn by females. Fort and Varney (1989), who also administered the DAST, found that among the 1,600 drawings from students in grades 2–12, only 135 of the pictures included female scientists. Furthermore, only six of these pictures were drawn by males. Huber and Burton (1995) also administered the DAST, and of the 223 students aged 9–12, 72 of the students drew female scientists. Of these 72 pictures, only 13 were drawn by males. When administering the Draw an Engineer Test (DAET) to students in grades 3–12, Knight and Cunningham (2004) found that of the 64 students, 61% of the drawings were of males and 39% of the drawings were of females. Further, like the DAST, most of the drawings of female engineers were found to be drawn by females. The results of these studies indicate that although over time more students, including more male students, perceive scientists to be female, the stereotype of scientists as being primarily male is prominent among students.

Another line of research focuses on the role of stereotype threat, which is expected to have a powerful influence on an individual's motivation and achievement (Smith 2004). Stereotype threat, which involves the risk of confirming a negative stereotype about one's group, is described a great deal in the research in mathematics education as a factor influencing gender differences in achievement (e.g. Inzlicht and Ben-Zeev 2000). Although fewer studies have examined stereotype threat in science, the research that exists suggests that it is a problem. For instance, when testing physics and engineering students at the college level, researchers have found that when stereotype threat was high (the stereotype that females are not as good in science is made salient) females performed more poorly than males on the test. However, when stereotype threat was removed (informing students that the test is gender-fair), females performed as well as males (Bell *et al.* 2003).

Females may not be motivated to pursue careers in the physical sciences because these careers are not perceived as people-oriented type professions (Morgan *et al.* 2001). Female college students are significantly more likely than male students to choose careers that allow them to help and interact with people, whereas male students are significantly more likely than female students to choose careers that offer high pay and status (Jones *et al.* 2000; Morgan *et al.* 2001). Females may find careers in physics, engineering, and computer science less interesting than do males if they perceive these careers as offering fewer opportunities for helping and working with others. Medical careers offer opportunities for high pay and status, similar to careers in the physical sciences, but also offer opportunities for helping and interacting with others. It is likely for this reason that when women choose to enter science-related careers that they tend to pursue medical professions (Lupart *et al.* 2004).

The research on gender differences in motivation can inform the research on expertise. The research suggests that beliefs about competence, personal values, and perceptions of who does science appear to be critical in determining whether students are motivated to pursue the sciences. Poor motivation may result in females being less likely to engage in the practice needed for expert performance. Combined with poor social support providing motivational support and feedback, females may find themselves particularly disadvantaged.

There have been many efforts to provide support for females in physics. This can be seen in the physics for girls programs designed to support the motivation and learning of young females in physics. The Summer Girls Program, offered by the physics department at the University of Maryland and sponsored by the National Science Foundation (2006) is an example of one of these programs designed for eighth and eleventh grade females. The young females attend a 2-week program in which they listen to lectures, see demos, write in journals, conduct hands-on experiments in physics, and apply the principles they learn to the design of working models of roller coasters. Further, the girls have the opportunity to fly as part of learning about aerodynamics. Another program, the Women of Texas Instruments Fund, developed by senior women at Texas Instruments, is a summer program aimed at increasing high school females' interest in physics by engaging students in authentic hands-on experiences in physics (Riley 2005). Although these programs improve females' motivation, there is no evidence that these programs improve achievement. We need to know how these programs support the transition towards more expert performance.

Enrollment and experience

Although not described in the expertise research in physics, the general framework of expertise indicates that the development of expertise is strongly linked to the willingness to devote time and effort to deliberate practice (Ericsson 1996). The more practice one gets, the better one gets, regardless of innate talent and ability. Experts differ from novices in the amount of time they spend working in a domain with experts spending considerably more time learning and improving skills and knowledge (Ericsson 1996). The research on gender differences in science seems to support the expectation that expertise requires considerable practice. In science, males take more classes and have more hands-on experiences than do females (Shin and McGee 2002), particularly in physics, likely contributing to their higher achievement.

Females take fewer science courses in high school and college, particularly physics courses (e.g. Murphy and Whitelegg 2006; NSF 2006; Seymour and Hewitt 1997), and this creates a disadvantage for them in their course grades (e.g. Hazari *et al.* 2007), and on achievement tests (e.g. Burkam *et al.* 1997). For instance, high school females tend to take fewer elective and advanced physics courses, as well as mathematics courses needed to be proficient in physics (e.g. Murphy and Whitelegg 2006; NSF 2006). Specifically, high school females are less likely than males to take Calculus, AP Calculus, Physics, and AP Physics (NSF 2006). The failure of females to enroll in science classes would make it less likely that they would pursue a science career (National Commission on Excellence in Education [NCES] 2000). Although gender differences in performance on science achievement tests can be partially accounted for by differences in course work, the gap is not eliminated when this variable is held constant (Burkam *et al.* 1997). This suggests that although encouraging females to take more science courses will have some payoff in the form of increased participation in science and higher performance on achievement tests, it will not completely eliminate gender differences in science achievement.

Differences in experiences do not stop with gender differences in enrollment. When males and females enroll in the same courses they have very different experiences. In science classrooms, males tend to have more hands-on experiences. In elementary through high school science classrooms, males are more likely than females to be active participants when conducting experiments (e.g. Desouza and Czemiak 2002; Jones and Wheatley 1990; Shin and McGee 2002). For instance, Shin and McGee (2002) found that when working in groups with physical science materials, high school males tend to be the ones who work with the lab equipment and direct activities, whereas females tend to play the role of recorder. Further, males are much more likely than females to work with batteries, microscopes, and electric equipment inside, as well as outside of class (e.g. Jones *et al.* 2000); these differences in hands-on experiences appear to reflect gender differences on science achievement tests with males excelling in the physical sciences. At the college level, Seymour and Hewitt (1997) found that female participants seemed to approach laboratory tasks with more uncertainty than did male participants. Seymour and Hewitt believed that these results reflected a deficit in hands-on or laboratory experiences in the females' precollege education. If Ericsson (1996) is correct and the amount and quality of exposure to the domain is critical for the emergence of expertise, then females have a clear disadvantage starting in elementary school.

Differences in course work and hands-on experiences taken in combination with gender differences in social support and motivation likely go far in explaining why females do poorly in comparison to males in physics and other domains of science. The gender literature provides little insight, however, on the impact these more distal factors have on proximal factors such as conceptual knowledge and problem solving strategies needed for successful, expert performance in physics.

New Directions for Research on Gender Differences in Science

There are gaps in both the research on the development of expertise in physics and the research on gender differences in science. Filling these gaps and connecting theory about how gender differences develop in physics with theory about how expertise develops would inform both areas of research. Below we make recommendations that we hope will improve the work on expertise and result in a better understanding of why females do not do as well as males in physics. We make three key recommendations including (1) the need to understand the failure to achieve expertise as being caused by multiple, interacting variables, (2) the need to take a developmental perspective on expertise and gender differences in science, and (3) the need to look more closely at the role of authentic experiences in the development of expertise and as an explanation for gender differences. We hope that our recommendations result in changes in the research on expertise in physics as well as the research on gender differences.

A need to focus on the interaction of multiple variables

The current research on gender differences in science touches on a number of possible causes, including lack of teacher and parental support, lack of motivation, a tendency to avoid science courses, and a lack of hands-on experiences. Although there are gender differences in each of these potential causes, the lack of over-arching theory connecting these differences to the emergence of expertise makes it difficult to conclude that it is these factors that determine whether females achieve in and pursue the sciences. We do not know whether or how these factors work together to influence the development of expert performance. Furthermore, no connection has been made between these more distal contributors to expertise and the more proximal indicators of expertise including the more expert problem solving strategies and conceptual understanding of experts. We need to know how these variables described by the expertise research and those described in the gender literature interact to result in females opting out of physics and other sciences.

A developmental focus is needed

Neither the expertise literature nor the gender literature takes a developmental perspective. We do not know how the variables described in the gender differences research and those described in the expertise research in physics influence each other's development as students move from novice to expert status. The expertise literature in physics is particularly problematic in this regard. What we have from this research is a snapshot of experts in a problem solving situation. We do not have an understanding of how these experts progressed towards expert performance. A developmental perspective would provide an understanding of how experts are created, and how variables such as motivation, deliberate practice, and social support influence the transition to expertise within physics.

The bulk of the research examining gender differences in science, including physics, examines these differences among students in grades K-12, whereas the research comparing novices and experts in physics focuses primarily on university level students and faculty. We know little about how the factors examined in the K-12 years influence gender differences during adulthood. Nor do we understand the early precursors to later developing scientific expertise. The research from the work on gender differences suggests that expertise may have its roots early in elementary school as a function of early experiences with physics and the social support children have during these early experiences. Ideally, future research on gender differences would use of an expertise framework with a developmental focus. Such a line of research would provide insight into how the path to expertise can be negatively influenced as in the case of females, and how expertise can be better supported for all students.

A developmental perspective would also allow us to determine which variables are most important, and at what time. Different variables may be important at different times. A developmental perspective would not only provide a better understanding of how expertise develops, but would provide insight into what variables should be focused on at different time points.

A more authentic view of expertise is needed

One major limitation of the expertise literature in physics is that it fails to explain and describe expertise as it develops and functions in the real world (Anzai 1991). Physics professors at a top physics department (UC Berkeley), for example, were not able to solve all problems in introductory courses (Reif and Allen 1992), but this does not mean that they are not experts. The research on expertise needs to go beyond performance on relatively simple tasks. Expertise is best assessed using authentic and complex tasks that experts, such as physicists, typically perform (Ericsson 2006a, b; Roe 1956) and that better discriminate expert from novice performance. These tasks include research problems that, due to their complexity, frequently take weeks, months, or even years to solve. Such a line of research would examine performance on multifaceted, complex tasks that truly define expertise. Within the domain of physics, there is only a small body of research that examines authentic and complex problem solving at the high school and college level, and this research almost exclusively uses interest as the outcome variable and does not compare individuals of varying levels of expertise (e.g. Kaschalk 2002). This research, therefore, does not tell us much about the importance of authentic experiences for the development of expertise.

Research needs to examine gender differences in willingness to engage in the many hours of practice needed to solve more complex and authentic physics problems. The research on gender differences suggests that females may be less likely to possess the motivation needed for deliberate practice in physics. However, male and female musicians seem to be equally willing to engage in many hours of solitary practice (Ericsson *et al.* 1993). This suggests that the ability to engage deliberate practice is not an issue. The question is whether females are willing to engage in such practice in science, particularly within the domain of physics. It is clear from the research on the dropout rates for females in science that we need to look at the factors that suppress females' willingness to devote the time needed for deliberate practice and the development of expertise.

We argue that it is important to determine whether females differ from males in basic problem solving skills and knowledge. We do not make this argument on the assumption that teaching females to use more advanced strategies and to draw pictures during problem solving is likely to make them experts. Instead, although incomplete, the literature on expertise is clear in illustrating the importance of qualitative and quantitative cognitive skills and knowledge for expertise. The literature on gender differences has tended to ignore this, focusing on motivational and social factors. Motivation and social influences are distal factors that influence the emergence and quality of more proximal factors including the quality of the knowledge base and strategies used. We argue that we need to know how motivation, cognition, and social influence interact to produce expertise.

We believe the framework we have proposed in this paper will provide useful information as to how female students' success in physics is derailed beginning in elementary school. This information can provide us with guidance as to how, when, and where to intervene to help support the development of physics expertise in females. This review also addresses serious concerns with the work that has been done and provides direction for the work that needs to be done. In particular, as individuals move from novice to expert they must take on the responsibilities and roles of experts including that of conducting high quality research and publishing. Research needs to be conducted examining how an expert in physics develops and thrives. For instance, for doctoral students, support from an advisor, support from family, deliberate practice, and certain cognitive skills (e.g. excellent mathematics skills) are likely crucial for success. We also need to know how this process may be stymied for females. This information could be used to refine the current framework of expertise. There is no research in physics, at this point, to guide these modifications of the framework.

In physics, women are underrepresented in academia, particularly at higher ranks (NSF 2004), and have fewer publications in the field (e.g. Rosser 2003; Schneider 1998). As of 2003, 13% of women received doctoral degrees in physics, and 95% of these women worked in academia. When examining the tenure and promotion ranking in physics departments across the United States, fewer women were found at associate and full professor levels. Specifically, 16% of women were assistant professors, 11% were associate professors, and 5% were full professors in 4-year colleges and universities (NSF 2004). Further, of the 178 individuals who have received a Nobel Prize in physics from 1901–2006, only two of these recipients have been women, with the most recent being awarded in 1963. It is important to determine what factors are most important for influencing expertise at graduate and professional levels so that women and men both have the opportunity to achieve at the highest levels in their fields.

We believe examining gender differences in physics using an expertise framework will provide useful information as to how female students' success in physics is derailed. Much more research needs to be done, however. The research on expertise in physics needs to be expanded to examine social and motivation influences on the emergence of expertise. In addition, the research, and the theoretical framework on which it is based, needs to take a developmental approach, in which variables are understood to interact and influence each other's development. Finally, a more authentic view of expertise is needed. This information can provide us with guidance as to how, when, and where to intervene to help support the emergence of expertise in females, could help prevent developmental delays in the emergence of expert knowledge and skill in females, and ultimately help to minimize the large gender gap in achievement and participation in physics.

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