Chapter 10
Gender Differences in Spatial Ability: Implications for STEM Education and Approaches to Reducing the Gender Gap for Parents and Educators

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10.1 Introduction

10.1.1 Overview of Gender Differences

The existence of gender differences in cognitive ability is a controversial topic. Nevertheless, researchers in psychological and the social sciences widely acknowledge that males and females differ in spatial ability (Halpern and Collaer 2005; Kimura 2000). Indeed, it is one of the most robust and consistently found phenomenon of all cognitive gender differences (Halpern 2011; Voyer et al. 1995). While there is individual variability within each gender, on average males score higher than females on tests that measure visual-spatial ability. However, there is considerable debate over just how large the differences between males and females are. Researchers also differ in their perspectives on the origins of the gender differences, including the relative contributions of biological, social and cultural factors. This chapter provides an overview of the research literature, as well as covering the developmental and educational implications for children.

Many researchers posit that early expertise in spatial ability in children lays down a foundation for the development of quantitative reasoning, a collective term encompassing science and mathematics. These researchers argue that the early differences in spatial ability have important implications for student achievement in STEM (science, technology, engineering and mathematics) subjects, and may partially explain the underrepresentation of women in science. However, while some

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children may be naturally gifted in spatial ability, there is a large body of research showing that spatial proficiency can be improved through relatively brief interventions. A growing number of educational psychologists have argued that early education of spatial intelligence is necessary as a matter of equity for all students, and that it may offer substantial benefits for the later development of mathematical and scientific skills across all ability levels (Halpern et al. 2007). We review interventions aimed at increasing spatial aptitude, and the role of parents and teachers in encouraging the development of these abilities.

10.1.2 What Is Spatial Ability?

The term “spatial ability” (also referred to in some research as visuospatial or visual-spatial ability) encompasses a range of different skills and operations, so it is important to clearly define the term. Laypeople can sometimes use the term very loosely, covering anything from block building assembly to reading maps and navigating one’s way around the city streets. Such tasks often incorporate additional (non-spatial) processes, including memory and general problem solving skills. Psychologists and cognitive researchers apply the term spatial ability to tasks that are intended to measure specific cognitive processes in isolation. Linn and Petersen (1985, p. 1482) defined spatial ability as the “skill in representing, transforming, generating and recalling symbolic, non-linguistic information”. More generally, it is the ability to perceive and understand spatial relationships, to visualize spatial stimuli such as objects, and to manipulate or transform them in some way – such as mentally rotating an object to imagine what it might look like viewed from a different angle or perspective. Spatial ability is crucial to a wide variety of traditional occupations including architecture, interior decorating, drafting, aviation, as well as a growing number of new and emerging occupations in the science and technology fields.

Spatial ability encompasses a broad range of cognitive processes, with the size of gender differences varying depending on the type of task (Voyer et al. 1995). When measuring spatial ability, some tasks measure global spatial skills such as wayfinding and navigation in virtual environments or outside the laboratory (Lawton and Kallai 2002). More commonly, specially designed tasks are employed to tap one or more spatial components in isolation. Linn and Petersen (1985), in a pioneering review of the literature, outlined three distinct categories of spatial ability. Firstly, we have *spatial perception*, which involves perceiving spatial relationships. A commonly employed task of spatial perception is Piagetian Water Level Task, which requires individuals to draw the waterline on a variety of containers or bottles that have been tilted a certain number of degrees (see Fig. 10.1). Another is the Judgment of Line Angle and Position test (JLAP), which requires subjects to correctly judge the orientation of a series of tilted lines (see Fig. 10.2).

The second category of spatial tasks is *mental rotation*. Tasks measuring mental rotation involve requiring individuals to mentally rotate spatial objects to see how they would look from a different angle or perspective (see Fig. 10.3). Mental rotation

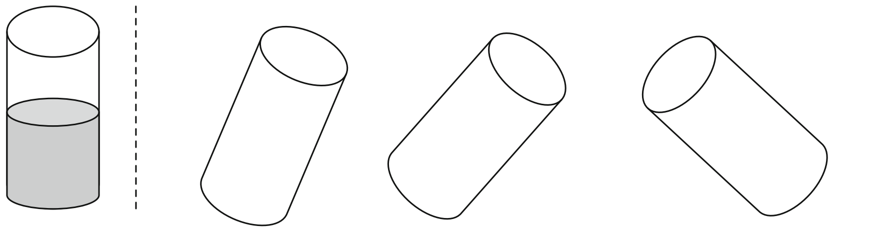

Fig. 10.1 In the Piaget water level task (Vasta and Liben 1996), subjects are presented with a container of liquid (*left*), with varying quantities of fluid. The container is then tilted adjacent to the horizontal plane. Subjects must then draw a *line* to indicate the probable water line in each of these containers

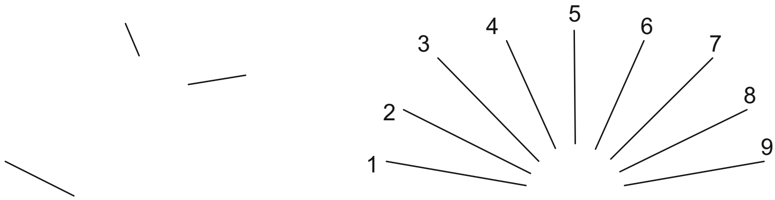

Fig. 10.2 Representative stimuli for judgement of the Judgment of Line Angle and Position test (JLAP; Collaer et al. 2007). Subjects must match the orientation of stimuli lines (*left*) to a reference array (*right*). The correct answers from left to right are 2, 4 and 9

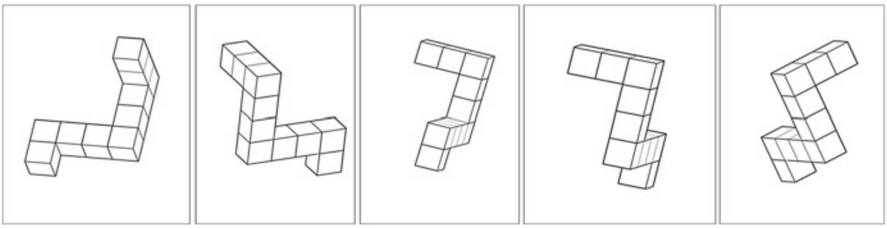

Fig. 10.3 Sample stimuli from the Vandenberg mental rotation task (Vandenberg and Kuse 1978). Subjects must locate both instances of the target shape (*left*) amongst the four possible choices. Two of the choices are mirror image distractors. To answer the question correctly, both targets must be located. The correct answer is 1 and 3 (From Peters and Battista (2008). Used by permission)

tasks usually involve three dimensional stimuli (Kimura 2000), though some tasks use less complex two dimensional stimuli (Prinzel and Freeman 1995).

The third category of spatial ability is *spatial visualization* which involve more complicated multistep manipulations of spatial information in order to reach a solution. These tasks often incorporate some element of spatial perception and mental rotation. They are distinguished by having multiple solution strategies for reaching a solution. Common tests of spatial visualization include the Embedded Figures

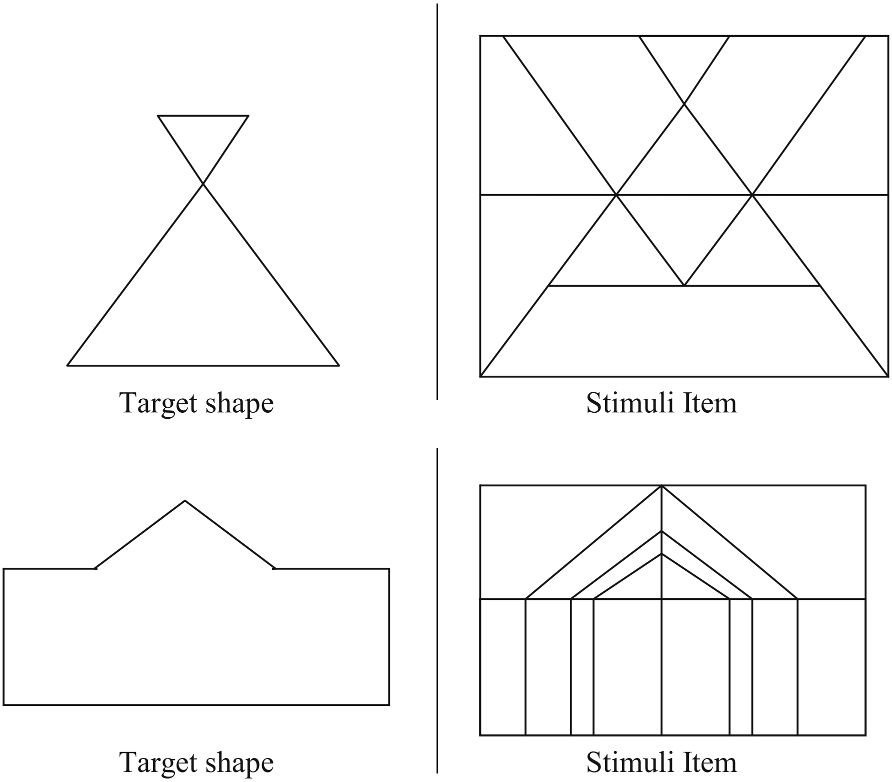

Fig. 10.4 Spatial visualization items representative of those used in embedded figures tasks (Witkin 1971). Subjects are asked to locate a target shape (shown on the *left*) within a more complex picture (*right*)

Test (EFT; see Fig. 10.4), which requires individuals to search for a target shape within a more complex picture of geometric shapes and to ignore distracting visual information. Another task is the Paper Folding task, which requires individuals to visualize how a sheet of paper would appear if it were folded in a certain way and then one or more holes were punched through the folded sheet. Individuals must indicate how the unfurled paper would appear and indicate the position of dots from a series of possible answers (see Fig. 10.5).

Some researchers have proposed a fourth category called *spatiotemporal ability*, which involves making time-to-arrival judgments or tracking the movement of an object through space (Hunt et al. 1988). Such tasks are computer administered in order to accurately measure response times and determine whether there are discrepancies between projected and actual arrival time (see Fig. 10.6). Other tasks involve directing the path of multiple objects concurrently (see Fig. 10.7; Contreras et al. 2001, 2007). However, it is unclear whether the gender difference observed with these tasks is necessarily spatial in nature, because there is some evidence that

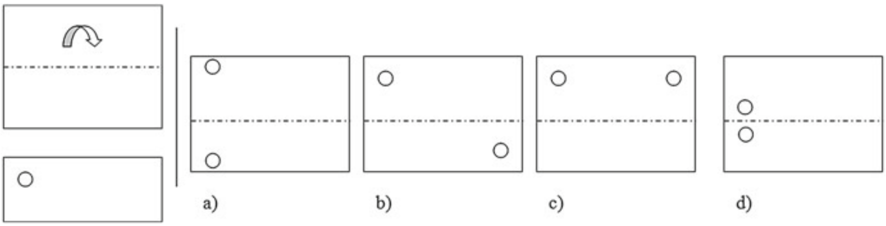

Fig. 10.5 Representative stimuli for a paper folding task (French et al. 1963). On the left, we have a blank sheet of paper with the fold line indicated (*top-left*). A hole is punched through the folded sheet of paper (*bottom-left*), and then subjects are asked to indentify which of the choices would represent the unfurled paper. Correct answer is d)

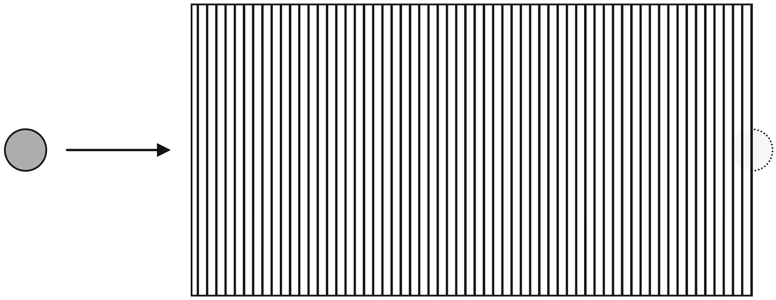

Fig. 10.6 An example of dynamic spatial ability task proposed by Hunt et al. (1988) requires subjects to judge the velocity of a target object as it moves behind an obscured view, and to press a key when they believe the object will emerge

males are more accurate in time perception generally (Hancock and Rausch 2010; Rammsayer and Lustnauer 1989).

10.1.3 Statistical Methods for Evaluating Gender Differences in Research

Experiments in psychology make heavy use of sampling, as it would be impractical to collect a measurement from *every* member of a given target population.

When a sufficiently large number of people are recruited, statistical tests can be performed to determine the probability that the observed group differences are due to chance, or whether they are likely to be found again if the experiment was repeated. If the probability that the results of the study occurred by chance is very low, the result is said to be *statistically significant*. Because research involves volunteer participants giving up their valuable time, and the time of the investigator to supervise data collection, researchers generally seek to minimise the number of participants involved. When extremely small sample sizes are recruited for a study

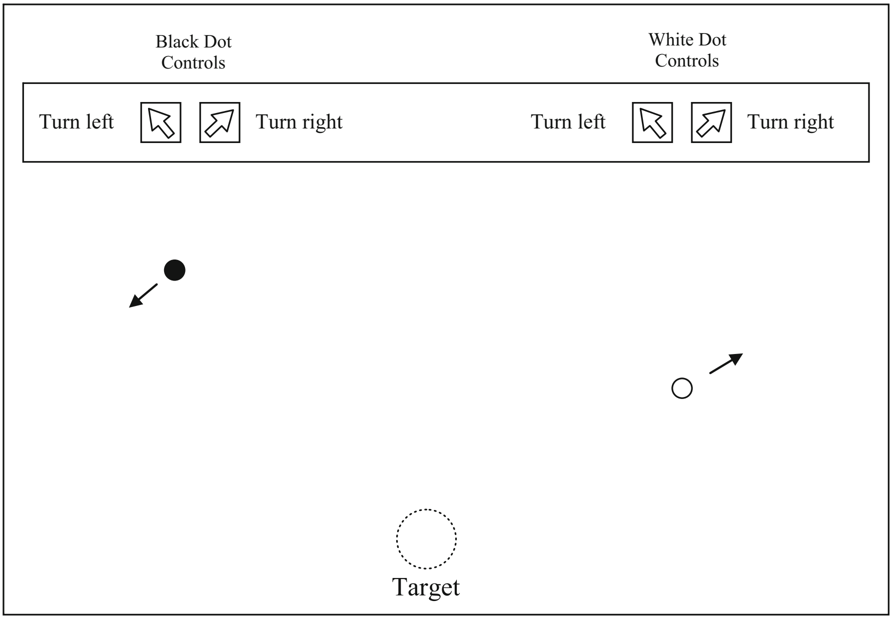

Fig. 10.7 Dynamic spatial ability requires subjects to steer two concurrently moving objects to a fixed destination point by clicking on the turn left and turn right buttons. *Arrows* show motion path of the *black* and *white dots*. Representative of the Spatial Orientation Dynamic Test – Revised (SODT-R; Contreras et al. 2007)

it may be lacking in statistical power (the ability to detect a statistically significant effect in a given sample, if indeed the effect in question is genuine). Furthermore, samples may differ in important characteristics, such as age, socioeconomic status, level of education, which may affect the study outcomes, serving to increase or diminish the magnitude of any group differences between males and females. By pooling the data from many studies, statistical power is increased and the researcher can arrive at a more reliable estimate of the true size of a given effect than could be reached from any individual study.

Meta-analysis is a statistical technique employed to summarize research findings across studies. Meta-analysis uses statistical methods to quantify effects across studies in an open and transparent manner, rather than simply comparing the tally of positive to negative studies (referred to as 'vote counting') or presenting a subjective interpretation of the scientific literature. For example, a selective review of spatial literature by Caplan et al. (1985) made the surprising claim that gender differences in spatial ability were diminishing and were no longer reliably found. A subsequent meta-analysis by Linn and Petersen (1985) provided strong quantitative evidence in a review of the *entire* published literature of the time that refuted such claims. Statistical techniques and software have advanced sufficiently in recent times so that it is now possible to test additional hypotheses about potential moderators, such as whether gender differences are diminishing in size across decades, or whether gender differences are present at certain developmental ages (such as childhood and adolescence).

When comparing two groups (such as males and females), the size of the effect in question is represented using a metric. A commonly used metric is Cohen's *d*, which represents the mean difference between two groups divided by the pooled standard deviation. The use of a common metric facilitates comparisons across different types of tests and samples, in a way that just reporting the mean difference could not. Cohen (1988) offered a set of guidelines for interpreting the magnitude of these group differences, suggesting that an effect size of $d < 0.20$ could be considered a "small" effect, values of approximately 0.50 could be considered medium in size, and values of 0.80 or greater would be considered large in magnitude. These benchmarks offer even the non-statistician assistance in determining whether the effect in question is *practically significant*, holding research to a higher standard than statistical significance alone.

10.1.4 How Large Are Gender Differences in Spatial Ability?

The meta-analytic review conducted by Voyer et al. (1995) represented the most comprehensive meta-analysis of the research on gender differences in spatial ability published at that time. The review categorised tasks by age, comparing children (under 13 years), adolescents (13–18 years), and adults (over 18 years). Mental rotation tasks showed the largest gender differences ($d = 0.33$ for children, $d = 0.45$ for adolescents and $d = 0.66$ in adults) followed by spatial perception ($d = 0.33$ for children, $d = 0.43$ for adolescents and $d = 0.48$ in adults). Spatial visualization showed the smallest gender differences ($d = 0.02$ in children, growing to 18 for adolescents and $d = 0.23$ in adults). By Cohen's guidelines, these would be medium-sized gender differences for mental rotation and spatial perception and in the case of spatial visualization tasks, relatively small. Contrary to earlier claims (e.g. Caplan et al. 1985), there is little substantive evidence that gender differences in visual spatial ability have greatly diminished over time though. Furthermore the gender differences follow a developmental progression from relatively small gender differences in childhood towards much larger gender differences in adolescence and adulthood. Though a meta-analysis has not yet been conducted on the type of spatial task called spatiotemporal ability, effect sizes in such studies typically fall in the medium to large range also (Halpern 2000).

10.1.5 When Are Gender Differences in Spatial Ability First Observed?

Gender differences in spatial ability are observed early. Children in primary school show meaningful differences across a range of spatial tasks including mental rotation and spatial transformation (Lachance and Mazzocco 2006; Levine et al. 1999). Indeed, some studies have even observed small sex differences in young infants when simplified tests of spatial reasoning are employed (Moore and Johnson 2008; Quinn and Liben 2008). However, the gender gap in spatial ability does appear to widen around the time of puberty, which some had claimed supported arguments for a biological and hormonal contribution. Correlation by itself does not necessarily prove *causation* though, as there may be other factors that co-vary with puberty. For example, as developmental researchers would also point out, this is time of increased gender conformity and strengthening of sex-roles (Ruble et al. 2006), as well as greater gender differentiation in play and leisure activities which provide opportunities to practise spatial skill (Baenninger and Newcombe 1989). Even after puberty the gender gap continues to widen, with somewhat larger effect sizes found in adults than adolescents. There is evidence that input and practice is required to fully develop spatial ability (Baenninger and Newcombe 1995), and the increase noted in puberty and in later adulthood may reflect the accumulation of social influences across time rather than the influence of hormonal changes.

10.2 Spatial Ability and Quantitative Reasoning

Spatial ability is thought to underpin the development of quantitative reasoning skills such as mathematics and science (Nuttall et al. 2005; Uttal et al. 2013b), which are important educational objectives. Factor analysis (a statistical technique used to investigate the relationship between tests) of cognitive ability tests show high loading for mathematical performance against a spatial factor (Bornstein 2011; Carrol 1993; Halpern 2000). Wai et al. (2009) note that a large body of research over the course of over 50 years has established that spatial ability plays a crucial role in stimulating the development of quantitative reasoning skills. For example, spatial reasoning is important for understanding diagrams of complex scientific concepts and principals, but individual differences in spatial ability predict learning outcomes with such media in physics and chemistry (Höffler 2010; Kozhevnikov et al. 2007; Wu and Shah 2004). When engaging in complex problem-solving tasks in science and mathematics, students who use spatial imagery and diagrams perform better than students using verbal strategies (Spelke 2005), and growth in spatial working memory is positively correlated with mathematics proficiency (Li and Geary 2013).

Furthermore, performance on measures of spatial ability are predictive of future scholastic achievement in mathematics and science, even many years later (Uttal et al. 2013b). Shea et al. (2001) reported the results of a 20 year longitudinal study that followed children from seventh grade through to the age of 33. They found that individual differences in spatial ability measured in adolescence predicted educational and vocational outcomes two decades later, even after controlling for preexisting mathematical and verbal abilities.

Another study by Casey et al. (1995) examined a large sample of U.S. adolescents preparing to sit the Mathematics Scholastic Aptitude Test (SAT-M) for college entry, an important prerequisite for entry into further education in mathematics and science. Performance on the Vandenberg Mental Rotation Task successfully predicted SAT-M entrance scores, even after controlling for general scholastic ability (Casey et al. 1995). Although still significant for males, the relationship between spatial ability and mathematics achievement was stronger for females suggesting that girls may be particularly disadvantaged by deficits in spatial reasoning. Casey et al. suggest that spatial ability acts as an important mediator in the gender gap in STEM achievement. Furthermore, they found that higher spatial ability was associated with greater self-efficacy beliefs about learning mathematics (Casey et al. 1997). Attitudes may exert a powerful influence on whether students decide to undertake further classes in mathematics and science (Ferguson et al. 2015; Simpkins et al. 2006), suggesting that there may be motivational effects as well as cognitive effects when spatial competencies are improved.

10.2.1 Importance of Spatial Ability for STEM

Educators, scientists, and policy makers acknowledge the importance of increasing mathematical and science literacy proficiencies for students generally. There is also evidence to suggest that the early gender differences in spatial ability may contribute to the later emergence of gender differences in mathematics and science (Ceci et al. 2009; Wai et al. 2009). Examination of historical scholastic achievement scores in the U.S. by Hedges and Nowell (1995) found that males, on average, have higher achievement scores in mathematics and science. Furthermore, when we examine the extreme right tail of the ability distribution, the gender gap is considerably larger. More recently, studies on data from the federal National Assessment of Educational Progress (NAEP) in the United States replicated these findings. For example, Reilly et al. (2015) observed small but stable mean gender differences in mathematics and science achievement and that at the higher levels of achievement boys outnumber girls by a ratio of 2:1 (Reilly et al. 2015). However gender gaps in maths and science are not inevitable. International assessments of educational achievement find that in some countries, females actually outperform males to a significant degree in mathematics and science (Else-Quest et al. 2010; Guiso et al. 2008; Reilly 2012).

A number of researchers have proposed that in order to address the gender gap in mathematics and science achievement, it is necessary to first address the gender gap in spatial ability (Halpern 2007; Newcombe 2007). Fortunately spatial ability is not a fixed and immutable trait (see the section "Interventions for Training of Spatial Ability"). In a review of educational research on gender difference, Hyde and

Lindberg (2007) argued that even a mild increase in spatial ability might have "multiplier effects in girls' mathematical and science performance" (Hyde and Lindberg 2007, p. 29). This is an important goal as a matter of gender equity, but we can also see substantial improvements of training for males as well. In a review of the developmental and educational research on spatial ability and STEM and the American educational system, Uttal et al. (2013b) argue that including spatial thinking in the science curriculum could substantially increase the number of students capable of pursuing STEM careers. Given that in many developed countries there are shortages within STEM occupations, addressing spatial proficiency in early education may be an important tool for improving overall mathematics and science literacy.

10.3 Theoretical Perspectives on Origins of Gender Differences

Halpern and Collaer (2005) described gender differences in spatial ability as some of the largest found for any cognitive task, raising the important question as to its developmental origins. Why do males on average outperform females on spatial tasks? Past approaches to this question have emphasized biological factors as well as social factors, cultural influences, and life experiences. It is unlikely that there is one single factor that can adequately explain the magnitude of the gender gap for spatial ability. Most gender difference researchers would acknowledge both biological and social forces contribute to their development, embracing a biopsychosocial model of gender differences (Halpern and Tan 2001; Hyde 2014). While there may be biological factors that predispose an individual to greater or lesser proficiency on spatial tasks, it must be remembered that they are not immutable. Full development of such skills requires practice and experience, and both males and females can make significant gains with training.

10.3.1 Evolutionary and Genetic Factors

Evolutionary psychology seeks to make sense of gender differences in human cognition by considering the role of evolutionary selection arising from the division of labour between men and women in traditional hunter-gatherer societies (Eagly and Wood 1999; Geary 1995). Men would be required to travel long distances in order to track and hunt animals, a task requiring strong spatial perception and navigation skills (Buss 1995, 2015). In contrast, women fulfilled the role of the gatherer of more local food and assumed childrearing duties. This role had less need for spatial proficiency but emphasized other adaptive traits such as nurturing and fine-motor skills. Over successive generations, evolutionary forces may have developed sex-specific proficiencies in spatial ability, giving males a strong advantage over females with such tasks (Buss 2015; Jones et al. 2003).

Support for the position of evolutionary psychology comes from cross-cultural studies of cognitive gender differences. Unlike language and quantitative reasoning which shows substantial variation across countries and cultures (Else-Quest et al. 2010; Lynn and Mikk 2009; Reilly 2012), a large body of research has shown that spatial differences are consistently found in all countries (Janssen and Geiser 2012; Peters et al. 2006). Furthermore intelligence – including spatial ability – is a highly heritable trait (Bratko 1996; Sternberg 2012), meaning that it can be passed down from one generation to the next. Nevertheless, some researchers question the validity of evolutionary and genetic factors (Hyde 2014), arguing that at the genetic level men and women are identical with the exception of the sex chromosome. Such arguments do not take into account other biological differences. For instance, the expression of sex hormones might be an important factor linked to genetic and evolutionary gender differences (Hines 2015a; Sherry and Hampson 1997).

10.3.2 Contribution of Sex Hormones to Spatial Ability

Sex hormones such as androgens and estrogens have been proposed as a biological explanation for observed gender differences in spatial ability (Kimura 1996, 2000; Sherry and Hampson 1997). While both males and females produce these sex hormones to some degree, greater androgen production is typically found in males while greater estrogen and progesterone production is present in females. Such a difference starts early, with differences in testosterone concentration of foetuses found as early as 8 weeks gestation (Hines 2010). Production of sex hormones greatly increases with the onset of puberty (Spear 2000), and is associated with a range of psychological and behavioural changes as well as differences in brain development (Berenbaum and Beltz 2011; Sisk and Zehr 2005).

Even before birth, sex hormones contribute to the organisation and development of the brain with lasting effects on behaviour and interests for children (Hines 2015a). Girls exposed to higher than normal levels of androgenic hormones prenatally, either due to a genetic disorder such as congenital adrenal hyperplasia or because androgenic hormones were prescribed to mothers during pregnancy, show increased male-typical play, behaviour, and interests as young children (Auyeung et al. 2009; Hines 2010). Furthermore, they perform at a higher level on tasks of spatial ability than their same-sex peers (Puts et al. 2008). Because spatial ability requires environmental input for development, toys and play can be an important source of spatial experiences. Many stereotypically masculine activities such as construction blocks and model building promote spatial development (Caldera et al. 1989; Caplan and Caplan 1994), and gender differences in sex hormones may influence boys and girls play preferences.

Sex hormones also play an activational role in human behaviour and cognition after the onset of puberty (Berenbaum and Beltz 2011; Spear 2000), which coincides with a widening of the gender gap in spatial ability (Kimura 2000; Voyer et al. 1995). There is an intuitive appeal to considering hormones as explaining part or all of the gender gap in spatial ability, but correlation by itself does not prove causation. Hormonal effects also coincides with increased gender conformity pressures for adolescents (Ruble et al. 2006) which may limit the interests and leisure activities that boys and girls pursue. These, in turn, may provide greater exposure to spatial experiences for boys than girls, thereby exacerbating gender differences.

To establish the causal effects of hormones would require an experiment whereby androgens were administered, which would be both impractical and unethical in developing children. There are instances where researchers have observed the effect of atypical levels of sex hormones (either reduced or increased levels) that are associated with certain medical conditions. Spatial ability in men diagnosed after puberty with hypogonadism is lower than in those with normal testosterone levels (Alexander et al. 1988; Hier and Crowley Jr. 1982), while men receiving hormone replacement therapy later in life showed significant improvements in spatial performance after treatment (Janowsky et al. 1994). In otherwise healthy individuals, some studies have also found a contribution of endogenous testosterone in the bloodstream to spatial performance in both genders (Davison and Susman 2001; Hausmann et al. 2009; Hromatko and Tadinac 2007), as well as fluctuations across the menstrual cycle in girls (Hausmann et al. 2000; Kimura and Hampson 1994). However, not every study finds robust associations (Puts et al. 2010), and the activational role that these hormones play may explain a much smaller proportion of variance in spatial ability than their earlier contribution to brain development (Falter et al. 2006).

10.3.3 Different Socialisation Experiences Between Boys and Girls

While biological contributions to spatial ability may explain some of the gender gap, many researchers argue that gender differences in early socialization experiences of boys and girls also play a significant role. Although there is certainly a contribution of biology, many theorists note that gender is socially constructed. From infancy and throughout childhood and adolescence, boys and girls experience the world differently, and are subject to different pressures and expectations (Lytton and Romney 1991; Martin and Ruble 2004). Boys and girls receive different messages about the suitability of particular toys from their parents, and elicit different styles of interaction during shared play with their parents, caregivers and siblings (Caldera et al. 1989). Children also acquire messages about gender expectations from their peers, and from their teachers and instructors once they have entered the educational system (Jacobs et al. 2002).

There are many different theoretical perspectives on the socialization of gender. For example, social-role theory proposes that psychological differences between men and women arise from gender segregation in men and women's social roles (Eagly and Wood 1999), while the social cognitive theory of gender development posits that gender development is the result of learned experiences that teach gender roles through a system of observation, reinforcement, and punishment (Bussey and

Bandura 1999). An exhaustive coverage of the many other theoretical perspectives on gender is beyond the scope of this chapter, so we highlight only those relating specifically to spatial ability.

10.3.4 Sex-Role Mediation Theory of Spatial Ability

As children develop, they acquire stereotypically masculine or feminine traits, behaviours and interests, a developmental process referred to as sex-typing (Kohlberg and Ullian 1974; Martin and Ruble 2010). However, there is also wide variability across individuals in the degree to which people integrate masculine and feminine traits into their self-concept and sex-role identity (Bem 1981; Spence and Buckner 2000). Highly sex-typed individuals are motivated to keep their behaviour and self-concept consistent with traditionally gender norms, including the expression of intellectual abilities (Bem 1981; Steffens and Jelenec 2011). Others may integrate aspects of both masculine and feminine identification into their self-concept, termed androgyny.

The sex-role mediation hypothesis proposes that a masculine or androgynous sex-role identity promotes the development of spatial ability (Nash 1979). This theory proposes a number of mechanisms, including self-selection of play and leisure activities throughout childhood and adolescence, self-efficacy beliefs and motivation to practise tasks that encourage spatial competency, and sex-role conformity pressures (Reilly and Neumann 2013). This hypothesis has been tested a number of times over the decades, and two meta-analyses have been conducted (Reilly and Neumann 2013; Signorella and Jamison 1986). Both find support for sex-role mediation on the most prominently tested visual spatial task of mental rotation, but the scope of such reviews are limited by the shortage of studies testing other components of spatial ability. More recently an empirical study by Reilly, Neumann and Andrews (2016) tested support for the sex-role mediation hypothesis across a range of visual-spatial tasks, including mental rotation, spatial perception and spatial visualization. Masculine sex-role identification significantly predicted performance in both males and females.

10.3.5 Gender Stereotypes About Intelligence and Spatial Ability

Children begin to exhibit cultural stereotypes about what constitutes “masculine” or “feminine” by their early school years (Blakemore 2003; Ruble et al. 2006). This extends to characterising particular scholastic subjects and intellectual interests as masculine or feminine. For example, mathematics and geometry (which encourage development of spatial ability) is seen as masculine while language and arts are seen as feminine (Nosek et al. 2002). Boys also report greater interest and higher motivation in mathematics – a finding that is replicated cross-culturally (Goldman and Penner

2014). Such stereotypes influence the way that men and women see themselves in relation to intellectual domains generally (Nosek et al. 2002), as well as their motivation to persevere when they encounter obstacles to learning (Meece et al. 2006).

While gender stereotypes may influence interest and motivation, they also shape perceptions of our abilities and self-efficacy. Despite there being no scientific evidence for gender differences in general intelligence, parents typically believe their sons are more intelligent than daughters (Furnham 2000; Furnham and Akande 2004; Furnham et al. 2002; Furnham and Thomas 2004). These gender stereotypes are quickly incorporated into children's own self-beliefs and persist into adulthood. A consistent finding cross-culturally is that when asked to rate their own level of general intelligence, males tend to estimate their intelligence level considerably higher than do females (for a meta-analysis see Szymanowicz and Furnham 2011). The effect size of this gender difference is not insubstantial, $d=0.34$. Males also rate themselves as more spatially competent than females, $d=0.43$, which is again a moderately sized effect.

Popular cultural stereotypes (e.g. Pease and Pease 2001) that women can't read maps or navigate without asking for directions do women a real disservice. Males in general are seen as more capable at performing spatial tasks by a significant degree (Halpern et al. 2011; Lunneborg 1982), and gender stereotypes can become self-fulfilling prophecies that undermine both interest in such tasks as well as performance (Steele 1997). Recognizing that spatial ability is not immutable, but that it can improve with learning and instruction is an important first step for any targeted intervention aimed at eliminating the gender gap and ensuring gender equity.

10.3.6 Differential Practice of Spatial Skills by Boys and Girls

Piaget (1951) was one of the earliest scholars to suggest that play is an important part of child development, helping to develop childrens' motor skills and spatial abilities. Boys and girls are typically encouraged by parents to engage in stereotypically masculine and feminine play consistent with their gender (Eccles et al. 1990), but boys and girls also express preferences for different types of toys themselves (Hines 2015b). For example, boys tend to show a preference for vehicles and weapons while girls show more interest in dolls. The effect size for this gender difference is extremely large, with one study in children aged 4–10 years finding an effect size of $d=2.0$ (Pasterski et al. 2005). While there is considerable gender segregation in the types of toys marketed to boys and girls (Blakemore and Centers 2005), it is difficult to separate how much these choices are culturally directed and how much of the preference is biologically based. Recall that early androgen exposure prenatally has been associated with male-typical toy and play preferences (Auyeung et al. 2009; Hines 2010), suggesting at least some influence on boys' and girls' choices. Indeed, this strong effect is even found amongst non-human primates divorced of human cultural traditions. Male primates express greater interest and play longer with stereotypically masculine toys such as balls, cars, and trucks while female primates preferred dolls and plush animals (Alexander and Hines 2002; Hassett et al. 2008).

Caplan and Caplan (1994) have argued that many stereotypically masculine toys and activities encourage the practice and development of spatial skills, while traditionally feminine play reinforces other culturally valued traits like communication and cooperation. For example, construction blocks and model assembly requires children to read 2D depictions of 3D objects and then find the correct spatial orientation of small and similar looking parts, while carpentry involves precise measurement of spatial relations and manipulation of parts. At earlier ages, toys like cars and trucks offer hands-on practice in visually tracking a moving object and judging the correct angle and speed to cause collisions. Girls play less on average with spatial toys than do males (Jirout and Newcombe 2015), and thus have less opportunities to practise these skills. Even if the effect of differential practice of spatial skills offers only a modest initial advantage to boys, the effect may grow larger as children enter adolescence and begin to self-select leisure activities and hobbies that they enjoy and are competent at performing. Activities such as carpentry, mechanics, models, and computer games would further enhance visual spatial skills.

There is strong evidence to support the theory that gender differences in spatial ability are at least partially influenced by differential levels of practice between boys and girls. Surveys and questionnaires measuring participation in spatial activities are positively correlated with performance on a range of spatial tests (Baenninger and Newcombe 1989; Chan 2007). However, it is equally plausible that people with high spatial ability may be the ones who want to engage in spatial activity in the first place (Baenninger and Newcombe 1989). It does seem likely that spatial activity experiences may be developmentally important in children (Doyle et al. 2012), and that differential levels of practice make some contribution.

10.4 Interventions for Training of Spatial Ability

A considerable body of evidence attests to the malleability of visuospatial reasoning, and that peak spatial ability is only reached with sufficient environmental input and experience (Baenninger and Newcombe 1995; Caplan and Caplan 1994). While biological and social factors may result in males starting with a modest initial advantage over females in spatial ability, it is important to remember that it is an acquired skill; people do not emerge *de novo* and become *Tetris* grand masters. There is an old joke that starts with the question “How do you get to Carnegie Hall?” – the punchline of course is “practice, practice, practice”. Like any other learned skill, if we receive training and do appropriate practice we can improve spatial abilities over time.

A large number of studies have examined the effects of brief training interventions to improve spatial ability. While there is wide variation in effectiveness, almost all such interventions show some improvement in spatial ability. With the large number of studies, training types, and choices of samples, the technique of meta-analysis can provide an objective quantitative assessment. But before turning to these reviews, theoretical issues need to be considered.

There are four important theoretical questions. First, does spatial training benefit all recipients equally, or are there differential rates of improvement for males and females? If spatial training was only effective in those who already have a moderate level of proficiency, its usefulness in addressing the gender gap would be limited. Second, do the effects of training transfer to all spatial tasks (thereby indicating an improvement in latent spatial ability), or only to tasks that are very similar or indeed identical to those used in training? Sims and Mayer (2002) have questioned whether the effect of spatial training might simply be the result of practice and familiarity, rather than genuine improvement in latent ability. For interventions to be genuinely useful, training effects must generalise to novel and unfamiliar spatial tasks. Third, do the improvements to spatial ability persist over time or are they short-lived? Fourth, do all types of training interventions work, or do characteristics such as the type and intensity of training matter?

Two meta-analyses have investigated the effect of brief spatial instruction and training interventions. The first, by Baenninger and Newcombe (1989) investigated the effects of training in studies that used a repeated measures design (i.e. subjects' initial performance on a spatial test is measured, a brief training intervention is offered, and then spatial performance is tested a second time). Their review included studies spanning a considerable range of years from the 1940s to the 1980s. They found that substantial improvements could be made to spatial ability after training, with an impressive effect size of $d = 0.70$ when tested on the same spatial measure that they were trained on, and a more modest effect size of $d = 0.49$ when more general spatial tasks were administered. This is an important distinction, because it shows that the effects of spatial training generalize well to other spatial tasks rather than being simply familiarity with the test content arising from repeated administration. The researchers also sought to test whether there was evidence of differential improvement between males and females, but found no significant gender differences. What the researchers did not address though is whether the improvements to spatial ability persist over time. Instead the authors considered the intensity of the training intervention, finding that multiple sessions over several weeks delivered meaningful improvement and that extremely brief or single session interventions showed less substantive benefits.

While the review by Baenninger and Newcombe (1989) makes an important contribution to the literature, a number of researchers have argued that changes in men and womens' roles over the past few decades should result in smaller gender difference over time (Caplan and Caplan 1994). When research becomes too dated, it raises the question of whether it remains applicable to current generations. More recently, Uttal et al. (2013b) conducted an extensive meta-analytic review of the empirical studies on spatial training from more recent years. Their meta-analysis also included a large number of unpublished studies (such as masters and PhD level theses). This is important because there might be a selection bias in the literature towards publishing only statistically significant findings while non-significant findings may be discarded, termed the file drawer effect in psychology (Ioannidis et al.

2014; Rosenthal 1979). A genuine test of the effectiveness of training interventions would also need to consider findings that might disconfirm the hypothesis.

Uttal et al. (2013b) considered a wide range of spatial training interventions, from explicit instruction and courses to playing video games and practising spatial tasks. The meta-analysis found that spatial training interventions were highly effective, with an overall effect size of $d = 0.47$ which is a medium-sized effect. Consistent with the earlier meta-analysis by Baenninger and Newcombe there was no evidence for differential improvement between males and females. Both genders gained the same benefits from training. Moderator analysis also showed no difference in the type of training being offered, with similarly sized effects across interventions that offered spatial learning courses, practice on spatial tasks or practice on video games. Adults also showed similar rates of improvements as adolescents, and though there was a slight tendency for interventions with children to have larger effect sizes, this trend did not reach statistical significance.

Another important research question about training interventions is whether the effects persist over time. Most studies that report the results of a spatial training intervention test subjects at the conclusion of the intervention, but a number of the studies evaluated in Uttal et al. (2013b) introduced a short delay of a few weeks and some tested subjects after as long as several months (Terlecki et al. 2011). If there were genuine and lasting improvements to latent spatial ability, we should see similarly sized effects of improvement between studies that tested performance immediately to those studies that included some latency. The meta-analysis found the effect of training to be durable, with no diminution of improvement for studies that introduced a delay before retesting.

To address the question of whether training interventions show generalisability to other types of spatial tasks, Uttal et al. (2013b) compared studies that used very similar measures of spatial performance to that covered in training with studies that employed substantially different types of spatial tasks. Importantly, the meta-analysis showed no difference between these two categories, providing evidence of transfer to novel tasks.

The research outlined above provides strong evidence that regardless of gender, spatial ability is highly malleable with instruction and training. Furthermore these effects do transfer to other types of spatial tasks and persist over time. Even brief interventions seem to have some effect, but more intensive training over multiple sessions yields the strongest benefits. Importantly the effects of training generalise across tasks, and improvements can be delivered for practically any age group from children to older adults.

10.4.1 Spatial Training and STEM Outcomes

While spatial ability is important for many occupations, the most compelling benefits of spatial training are in improving mathematical and science achievement in students. Longitudinal studies have provided compelling evidence of an association between spatial ability and proficiency in mathematics and science (Wai et al. 2010), but to date only a limited number of studies have investigated whether spatial training translates into tangible improvements in STEM achievement. Cheng and Mix (2014) conducted a randomized control trial of spatial training in a sample of 6- and 7-year old children, finding improvements in a test of basic calculation skills. A subsequent study by Krisztián et al. (2015) that taught spatial training with origami over a 10 week period in a sample of fifth and sixth grade students found similar improvements in computation skills over a control group. At present there are no spatial training studies that have measured science learning outcomes though in children, and none with adolescents in high school.

Amongst college-aged young adult samples, only two studies have investigated whether increasing spatial ability translates to improvements in mathematics and science learning. Sanchez (2012) conducted a randomized control trial that offered an intervention to target spatial ability, and found that the spatial group outperformed controls when tested on their learning from a short course on volcanoes and plate tectonics. In another study operating over a longer time period, Miller and Halpern (2013) recruited a sample of male and female first-year college students and randomly assigned them to either a control group or a spatial training condition (consisting of six 2-h spatial training sessions over a 6 week period). The gender gap in spatial ability narrowed somewhat after spatial training. In addition, the grades in student coursework were examined at the end of the year (up to 10 months after training ended). Compared to the control group, those receiving the intervention achieved higher grades in their physics coursework ($d = 0.32$) but not in other classes like chemistry or calculus. The study also found significant correlations between students' spatial ability and course GPA in the following sophomore year for a number of STEM courses, including electricity and magnetism, biology, engineering, and differential equations. The conclusions of this study are limited though by the small sample size for the treatment group (14 women, 24 men) which resulted in a reduced statistical power.

10.5 Reducing Gender Differences by Promoting Spatial Ability in Children

With the link between spatial ability and development of mathematics and science skills, a number of prominent educational and gender researchers have argued for the importance of developing spatial competency ability as a foundation for proficiency in STEM subjects (Hyde and Lindberg 2007; Newcombe and Frick 2010; Wai et al. 2009). With competing interests in a crowded curriculum, teachers and principals might be understandably reluctant to allocate time for regular lessons on promoting spatial competency. However, the effect of even brief training interventions over several sessions has been found to be effective in reducing the gender gap in spatial ability (Uttal et al. 2013a). Since both males and females can improve

Table 10.1 Summary of children's play and leisure activities providing spatial experiences

		Specific spatial abilities				
Age category	Play and leisure activity	SP	MR	SV	ST	WF
Toy and play experiences for younger children	Construction blocks	●	●	●		
	'Action-oriented' toys such as cars and vehicles	●			●	
	Geometric shape toys	●		●		
	Throwing and catching ball games	●			●	
	Jigsaws	●	●	●		
	Art and drawing activities	●		●		
	Mazes and maps	●				●
Enrichment experiences for older children	'Transforming' toys appropriate to age	●	●	●		
	Advanced construction bricks such as Lego™	●	●	●		
	Model building	●	●	●		
	Origami	●	●	●		
	Computer games (action)	●		●	●	●
	Computer games (puzzle)	●	●	●		
	Computer games (construction)	●	●	●		
	Perceptual and motor skills training such as juggling	●		●	●	
	Organised sports	●			●	●

SP spatial perception, *MR* mental rotation, *SV* spatial visualiztion, *ST* spatiotemporal, *WF* wayfinding and navigation

their spatial reasoning substantially, it might be applied broadly to all students, which avoids the potentially stigmatizing effects of singling out females as a group for special interventions.

While explicit training would benefit older students such as those in high school or entering college, Newcombe and Frick (2010) advocate the importance of early education for spatial intelligence *before* the gender gap widens. One approach would be to integrate spatial learning with existing content in the STEM curriculum. In a report by the American National Research Council (2006), a range of practical strategies are outlined for engaging students to think spatially as part of mathematics and science classes. Rich multimedia can present complex scientific concepts visually, and many electronic textbooks offer data visualizations that are interactive rather than being static displays. For example, force and motion concepts are difficult to convey verbally or from a printed diagram. By showing the motion path of a physical object, a child can see the effects of physical phenomena.

Parents and caregivers might also gently encourage spatial learning outside of school by providing children with play and leisure activities (outlined in Table 10.1) that encourage spatial development through attention to spatial relationships (e.g., higher–lower; longer-shorter; wider-narrower). Games such as jigsaws, construction blocks, and board games provide contexts that facilitate spatial learning. Newcombe and Frick also note that everyday conversation can also be an opportunity for parents to highlight the spatial properties of objects through questions and gently introduce spatial language and concepts into the conversation (Ferrara et al. 2011). Indeed, many household experiences can be learning opportunities to demonstrate spatial concepts, such as measuring and transformation of solids and liquids when moving ingredients from one container to another during cooking, or imagining what shape will be made if we fold a sheet of paper diagonally. Educational toys that provide examples of geometric shapes can be a good way to extend spatial language further by learning the names of common objects such as triangles, squares, circles, and relationships before introducing more complex shapes and concepts (Newcombe and Frick 2010).

Children as young as 3 or 4 years of age can understand the concepts of maps and how they relate to the physical world if introduced at the right pace (Shusterman et al. 2008), while puzzles like mazes can offer further practice of spatial and navigational skills (Jirout and Newcombe 2014). In older children, enrichment activities like jigsaw puzzles and origami can also provide additional opportunities to encourage spatial development (Boakes 2009; Taylor and Hutton 2013), particularly when parents and educators engage children in active conversation and provide guided assistance. Art and drawing activities can also provide practice in spatial perception and visualization skills (Calabrese and Marucci 2006). Age-appropriate toy robots that children can change into vehicles and back provides practice in learning complex multi-step transformations like that involved with spatial visualization, while a wealth of literature has shown that construction blocks provide opportunities to practise spatial perception and transformation skills (Caldera et al. 1999; Jirout and Newcombe 2015; Stannard et al. 2001). They also provide practice in interpreting two and three-dimensional diagrams, and then translating these diagrams into physical steps.

Another promising enrichment activity that aids in practising spatial skills may be video games. Computer gaming has emerged as a popular leisure activity for children and can be an opportunity to practise spatial skills. While boys still report playing more computer games than girls, in recent years the gap has been diminishing (Terlecki et al. 2011). Additionally, the wider availability of gaming on mobile phones and tablets may see shifts in gender patterns of usage. Not every player will enjoy first-person shooters or fast action games, and game developers are increasingly embracing other genres to entice non-game players into the market. However, not all games are equal, and some games may have greater educational potential than others. In a review by Spence and Feng (2010) on the contribution of videogame play to spatial cognition, action-based games and maze/puzzle genres emerged as the most likely to affect spatial cognition as they provide repeated practice in spatial perception, mental rotation, and navigation tasks. Indeed, a number of studies have shown that even brief training with computer games may be effective as an intervention (as reviewed earlier).

Parental concerns over the use of videogames may need to be considered if they are to be recommended. Concerns over violence in some types of videogames or excessive amounts of time spent playing remain legitimate (Festl et al. 2013). However, when enjoyed in moderation with parental selection of content there is evidence that the benefits for spatial cognition outweigh the costs (Ferguson 2007;

Uttal et al. 2013a). Parents may also be more comfortable offering less violent and adversarial games to their children, such as the popular construction and building game *"Minecraft"* which is appealing to boys and girls equally and is already used by some educators (e.g. Short 2012). Spence and Feng propose that gaming might also be an opportunity to deliver more targeted educational interventions specifically developed with the goal of raising spatial abilities in a similar fashion to commercial brain-training products.

There is also a strong link between the development of motor skills and spatial reasoning (Frick et al. 2009; Richter et al. 2000). Neuroimaging studies show that regions of the brain associated with motor skills are activated when performing mental rotation tasks (Halari et al. 2006; Richter et al. 2000). Interventions that consist of motor skills training have been shown to enhance mental rotation performance in children (Blüchel et al. 2013). Newcombe and Frick (2010) advocate that educators and parents should provide young children plenty of time for free play and physical action with objects like balls to provide practice in motor skills. By association, this should transfer into positive benefits for spatial ability.

Sporting activity and organised sports might also offer opportunities to more specifically develop spatial ability. While individual families may differ, sons typically receive greater encouragement to pursue athleticism and organised sports than daughters (Leaper 2005), and greater media attention and funding is given to male professional sports stars (Gill and Kamphoff 2010). In contrast, girls have lower enrolment in organised sports and withdraw from sporting teams at a higher rate (Vilhjalmsson and Kristjansdottir 2003). But there is evidence that playing sports may help to develop spatial ability (Moreau et al. 2015). When children who play regular sport were compared to similar aged matches who did not, those who played sport performed better on tests of spatial performance (Notarnicola et al. 2014), with similar findings in young adults (Lord and Leonard 1997; Moreau et al. 2011). Motor coordination is a significant predictor of mental rotation ability even after controlling for the effect of gender (Pietsch and Jansen 2012), and two studies have found that learning and practising juggling skills increased mental rotation performance for both adults and children (Jansen et al. 2009, 2011). Encouragement of sports activity within the context of the educational system and by parents may help to lessen the gender gap in spatial ability, in addition to the non-cognitive benefits (Moreau et al. 2015).

10.6 Directions for Future Research

Most researchers now endorse biopsychosocial models of gender differences in spatial ability (Halpern et al. 2007) rather than considering exclusively biological or social causes, and the debate has shifted towards their relative contributions. Whereas once spatial ability was considered fixed and immutable, a considerable body of research has demonstrated that exposure to new spatial experiences throughout early childhood promotes growth in spatial proficiency. Furthermore, spatial training interventions can produce substantial benefits that potentially could translate to a reduction or even the elimination of the gender gap in mathematics and science achievement.

As reviewed earlier, only a limited number of spatial training studies have measured subsequent outcomes in science and mathematics achievement outcomes however. To date though, there have been no spatial training interventions that have followed children longitudinally to follow their progress, and only a single study by Miller and Halpern (2013) has tracked the progress of college-aged students for a prolonged length of time. Arguments for spatial training interventions would be strengthened by further studies monitoring student progress over longer time periods. It would also allow investigators to determine what types of spatial training and at what intervals, will best deliver changes in STEM-specific outcomes. While brief interventions may well yield long-term improvement, it is also possible that spatial training will require maintenance "booster" training at periodic intervals to deliver lasting educational improvements.

10.7 Summary and Conclusions

While individuals may differ, on average males score higher in tests of visual spatial ability. They also rate themselves as more spatially competent than females. Gender differences in spatial ability emerge from an early age. While clearly observable in children, the gender gap widens in adolescence and continues to grow into adulthood where it is quite large. Gender differences are found for a variety of categories of spatial tasks, but the largest and most actively studied is mental rotation, followed by spatial perception and then spatial visualization skills. There are a range of theoretical perspectives on why gender differences in spatial ability develop from biology to environmental causes, but one of the most frequently argued causes is differential levels of spatial learning and practice between males and females. This is supported by retrospective studies finding associations between childhood spatial experiences and spatial ability in adults.

Gender differences in spatial ability also precede the development of gender differences in mathematics and science, and longitudinal studies have found that early performance on spatial tasks can predict future performance in STEM, even many years later. There is also robust evidence demonstrating that spatial ability is not an immutable skill, and that even brief interventions can deliver impressively sized improvements. Such evidence makes a compelling argument for integrating spatial learning into early education, but parents can also provide additional learning opportunities for their children by engaging in spatial language, demonstrating spatial concepts within the home, and providing toys and games that encourage spatial practice. In older children, computer games can provide an opportunity to learn and practise spatial skills if they express an interest them, and organised sports has also been shown to improve spatial ability. The research supports the conclusion that concerted efforts by educators to address the gender gap in spatial ability in children and adolescents may translate into improvements in girls' and boys' mathematics and science achievement. However there is a need for longitudinal studies to determine which types of training and at what intervals will best support students in this regard, and the extent to which this reduces the gender gap for STEM outcomes.

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