Review

The new science of cognitive sex differences

David I. Miller[1] and Diane F. Halpern[2]

[1] Department of Psychology, Northwestern University, Evanston, IL 60208, USA
[2] Department of Psychology, Claremont McKenna College, Claremont, CA 91711, USA

Surprising new findings indicate that many conclusions about sex differences and similarities in cognitive abilities need to be reexamined. Cognitive sex differences are changing, decreasing for some tasks whereas remaining stable or increasing for other tasks. Some sex differences are detected in infancy, but the data are complex and depend on task characteristics. Diverse disciplines have revolutionized our understanding of why these differences exist. For instance, fraternal-twin studies align with earlier literature to help establish the role of prenatal androgens and large international datasets help explain how cultural factors such as economic prosperity and gender equity affect females and males differently. Understanding how biological and environmental factors interact could help maximize cognitive potential and address pressing societal issues.

The new science of cognitive sex differences: contemporary societal issues, contemporary data

Controversial societal issues such as single-sex education and the underrepresentation of women in science and engineering fields have sparked new interest in and debate about sex differences in cognitive abilities. The idea of cognitive sex differences has captivated many people's curiosities and raises politically and emotionally charged questions. Can brain differences and testosterone explain why women and men perform differently on some cognitive tasks? Or can these differences be attributed to socialization practices and gender stereotypes? Recent evidence, emerging from diverse disciplines, has revolutionized our understanding of when these differences are found and why they exist. Research has confirmed some societal stereotypes, finding reliable and large sex differences on specific cognitive tasks [1]. Research has disconfirmed other stereotypes, finding compelling evidence for similarities between males and females on many cognitive tasks [2]. Moreover, even when average sex differences are large (Box 1), many individual men and women will disconfirm these group descriptions. These broad conclusions about sex differences and similarities have remained unchanged for many decades. However, surprising new findings, especially about trends over time, infant cognition, sex hormones, brain differences, culture, and stereotypes, indicate that other, earlier conclusions need to be reexamined. Building on comprehensive reviews [1,3], this review selectively focuses on these recent findings to highlight their relevance for understanding contemporary societal issues and informing policy decisions. These recent data are especially critical considering rapid changes in men's and women's participation in societal institutions such as higher education and employment. We focus on findings published within approximately the past 2–4 years and occasionally cite older studies to establish historical trends and meta-analytic findings. Earlier reviews [1,3] provide detailed discussion of other studies such as those concerning attitudes towards specific academic fields [4,5], biological sex differences more broadly [6,7], and socialization practices [8] including the effects of parental and teacher expectations [4,5].

Changes over decades

Research conducted in the 1970s to 1980s suggested an alarming finding that boys outnumber girls 13 to 1 among

Glossary

Androgens: hormones such as testosterone that influence some male characteristics such as the development of male genitalia.
Biopsychosocial: term that emphasizes the continuous, causal interactions between biological (e.g., brains) and environmental (e.g., activities) factors.
Cognitive sex differences: average differences in performance between females and males on tests of academic achievement and cognitive abilities.
Congenital adrenal hyperplasia (CAH): a genetic disorder that causes individuals to have abnormally high exposure to prenatal androgens.
Cortical thickness: the thickness of the cerebral cortex in a specific brain region. The cerebral cortex supports most cognitive functioning and is the outermost layer of the brain.
Gender: meanings that societies and individuals give to female and male categories.
Gender equity: structural factors that provide equal opportunities for men and women in different societal domains (e.g., education, workforce).
Gender stereotypes: beliefs such as 'women have poor mathematics ability' that associate women and men with particular traits. Some aspects of stereotypes are accurate, whereas others are not.
Meta-analysis: quantitative synthesis of empirical studies investigating a particular topic (e.g., sex differences in mathematics test performance).
Prenatal and postnatal: before and after birth, respectively.
Sex: grouping of people into female and male categories. Use of the term 'sex differences' does not imply that those differences are primarily biologically or environmentally caused.
Sex hormones: hormones such as estrogen and testosterone that influence some sex-differentiated characteristics such as reproductive functioning.
Stereotype threat: being at risk of confirming a negative stereotype about one's social group.

Corresponding author: Miller, D.I. (dmiller@u.northwestern.edu).
Keywords: sex differences; cognitive abilities; hormones; culture; stereotypes; education.

1364-6613/$ – see front matter
 http://dx.doi.org/10.1016/j.tics.2013.10.011

Box 1. What cognitive tasks show sex differences?

Some spatial tasks such as mentally rotating 3D objects show the largest sex differences, favoring men by ~0.5–1 standard deviations [26]. Much research has understandably focused on spatial tasks that show large sex differences, but this focus does not address how typical male advantages would be on a fuller range of spatial tasks. For instance, despite their presumed demands on spatial processing, geometry problems on mathematics tests typically show small-to-nonexistent sex differences [13,77].

Task characteristics influence spatial sex differences. For instance, male advantages in mental rotation are larger when the task involves 3D objects versus 2D objects [26] and has strict time limits versus no time limits [25]. However, other task differences are less well understood, such as why mentally rotating objects shows sex differences but mentally folding paper does not reliably (see Figure 1 in main text) [26,112]. For instance, Harris and colleagues recently reviewed comparisons between mental rotation and mental folding, finding evidence for many similarities in the underlying cognitive processes [112]. That review paper speculated that the differences in male advantages may reflect task differences in requiring rigid versus non-rigid transformations of objects, but noted that current evidence is limited.

At least one spatial task (remembering object locations) moderately favors women [22]. This finding aligns with small to moderate female advantages on some memory tasks such as remembering object identities, faces, and lists of words and numbers [11,18,22]. Some other memory tasks show more mixed findings [17,19–21]. For instance, when described as a test of geometry ability, a task involving recalling an abstract spatial diagram showed differences favoring boys ($d = 0.51$) [20]. However, when described as a test of drawing ability, the task showed differences favoring girls ($d = 0.50$). This study ($n = 199$) [20] replicated two earlier studies [19].

Sex differences in average mathematics test performance tend to be small to nonexistent [13,16,77], although boys outnumber girls among high performers (e.g., top 1% or higher) in most but not all nations [9,10,16,78]. These differences often do not reliably differ by task characteristics (e.g., geometry versus non-geometry problems), although girls sometimes slightly outperform boys on problems requiring algebraic solutions or short-answer responses [13,77]. These small female advantages for algebra and short-answer problems align with findings regarding verbal tasks. For instance, girls outperform boys in reading across the globe (~0.2–0.6 standard deviations) [11,16,79]. These female advantages are larger among lower-performing students [16,79] and are even larger for writing tasks [11].

Box 2. How do sex hormones influence cognitive ability-related brain development?

Influential theories in the 1980s hypothesized that cognitive sex differences can be explained by how much of the brain's left or right hemisphere is dominant for particular cognitive functions. Prenatal androgens were thought to slow development of the left hemisphere, resulting in males becoming more dominant than females in their right hemisphere. These lateralization sex differences could explain cognitive sex differences because verbal tasks often rely more on the left hemisphere and spatial tasks more on the right hemisphere [1]. However, four meta-analyses published within the past 5 years do not provide compelling support for these predictions regarding lateralization for language tasks [72,74,75] or hormone–brain relationships [71]. For instance, sex differences in lateralization for listening tasks are minimal ($d = 0.05$) [74]. Lateralization sex differences are sometimes found for spatial tasks [37,73], but these differences could reflect differences in strategies and experience [69,86] rather than the organizing effects of prenatal androgens. Adding additional complexity, prenatal androgens may not directly affect neural regions related to cognitive abilities but instead regions related to sex-typed preferences [42].

Postnatal hormones may influence brain development and functioning related to cognitive abilities, but the evidence is mixed. Some scholars have argued that moderate levels of androgens maximize spatial performance and therefore higher androgen levels should predict better spatial performance for females and worse performance for males [59]. Some evidence exists for these predictions regarding androgens encountered *in utero* [43,46], in puberty [62], and in adulthood [59,63]. However, other studies fail to support these predictions regarding androgens encountered in adolescence [52,56] or adulthood [54,61]. For instance, higher circulating levels of testosterone sometimes predict better spatial performance among adult men [54,61] or more complicated patterns [51]. Other correlational [55,56,58,60] and experimental studies [55,57], even those with moderately large samples ($n \geq 200$) [55,57,60], suggest that postnatal androgens have limited effects on adults' cognition. Puts and colleagues [60] concluded that 'circulating [testosterone] does not contribute substantially to sex differences in spatial ability in young men and women' (p. 282), based on a moderately large study with a within-subjects design ($n = 337$) and an extensive review of literature published in or before 2010. Studies on estrogens [51,55–58], older adults [55,57,58,61,63], and verbal abilities [53–58,61–63] do not indicate any clearer findings. These results may be consistent with the brain's sensitivity to sex hormones decreasing during adolescence [64,65]. Hormones may affect cognitive brain development during adolescence, but current evidence is mixed [52,56,62].

American students with exceptional mathematics talent [9]. However, this tail ratio has dropped to about 2–4 to 1 in recent years, according to both self-selected [9] and nationally representative samples [10]. Sex differences in average mathematics test performance also decreased during the 1970s to 1980s [11,12] and have since remained small to negligible [10,13].

These changes over time have led some scholars to conclude that cognitive sex differences are disappearing. However, the data indicate nuanced trends. For instance, the overrepresentation of males among high mathematics performers decreased during the 1980s, but has not been decreasing since the 1990s [9,10]. Since at least 1990, girls have earned higher mathematics grades by approximately 0.1–0.2 Grade Point Average (GPA) points [14]. Other data also indicate complex findings. Earlier meta-analytic evidence suggested few sex differences in verbal abilities [15], but recent analyses of large-scale international assessments call for reexamination of this claim. In an analysis of 1.5 million children's reading achievements, girls outperformed boys in all 75 nations in all testing administrations (in total, 213 independent samples) [16]. These sex differences were moderately large in 55% of cases ($0.36 \leq d < 0.65$) and may be increasing over time. Small-to-moderate female advantages are also consistently found for some but not all memory tasks (Box 2) [11,17–22]. Male advantages are found on some but not all spatial tasks (Figure 1) [22–26]; cross-temporal trends on spatial tasks are mixed [26].

Developmental trends

Some sex differences are found surprisingly early in life. For instance, in a large nationally representative sample, girls outperformed boys in reading by 0.2 standard deviations when entering kindergarten [27]. Although sex differences in average mathematics test performance are not reliably found until high school and college [13], small male advantages in high mathematics test performance (e.g., top 10%) are found among kindergarteners [28]. More dramatically, four studies have found male advantages

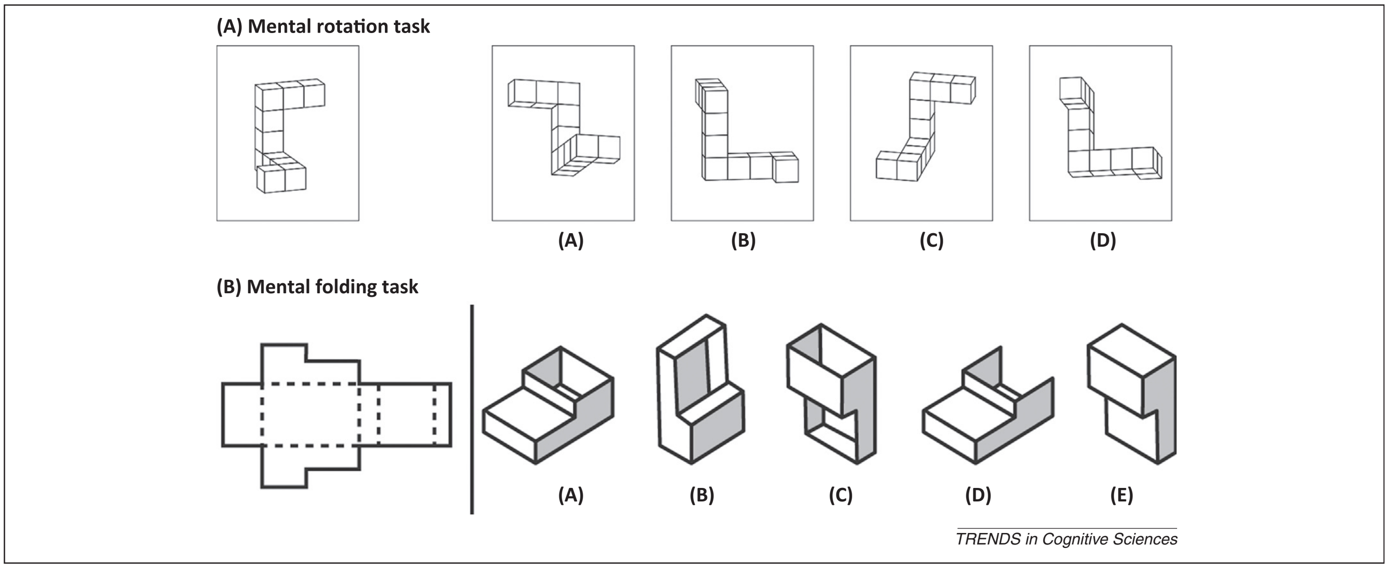

Figure 1. Example spatial tasks showing either large or small sex differences. For the mental-rotation task, participants are asked to mentally rotate the far-left object to match two of the right-hand objects (correct answers: B and C). For the mental-folding task, participants are asked to mentally fold the far-left drawing to match one of the right-hand drawings (correct answer: A). The mental-rotation task reliably shows large male advantages (~0.5–1 standard deviations), but the mental-folding task does not (~0.1–0.3 standard deviations) [26]. Reasons for this substantial variability across tasks remain a mystery [112]. Adapted, with permission, from [24] and [113].

in mental rotation tasks among infants as young as 3 months of age [29,30]. However, many other infant studies did not detect these differences when alternate mental rotation tasks were used [31–35], including tasks [34,35] that closely matched those used in prior studies [29]. Similar male advantages in rotation tasks are sometimes detected among preschoolers and kindergarteners [36–38] but sometimes not [39–41]. Causes for these nuanced differences across studies and tasks are currently unclear. Although often interpreted as reflecting innate brain differences, early-emerging sex differences do not necessarily establish biological or environmental causation. For instance, sex differences in high mathematics test performance are reversed (female advantage) among Latino kindergarteners, indicating the early emerging effects of family and culture [28]. Moreover, even infants' cognitive abilities are sensitive to small differences in experience (e.g., crawling, manually exploring objects) [31–35].

Hormonal influences

Much research on the cognitive effects of prenatal sex hormones has previously been limited to clinical populations, such as females with congenital adrenal hyperplasia (CAH) who are exposed to high levels of prenatal androgens *in utero* [42]. According to a meta-analysis of nine samples [43], females with CAH exhibit higher spatial performance than control females ($d = 0.47$). Recent research on nonclinical populations aligns with these CAH studies to provide converging evidence that prenatal hormones influence cognition. For instance, serving as natural experiments in nonclinical populations, females with fraternal male twins are also exposed to high levels of prenatal androgens [44]. These females also have higher mental rotation performance than control females ($d \sim 0.3–0.4$), according to two published studies ($n = 200$ and 471) and one unpublished study [45,46]. One study [45] also found that women with a slightly older brother (within 18 months of age) performed the same as women with a slightly older sister. This latter finding helps exclude the environmental confounds (e.g., presence of male-typical toys) that result from growing up with a male sibling close in age.

Females with fraternal male twins also show more male-typical patterns on a few other sex-differentiated traits such as sensation-seeking and tooth size [44,47], but not other traits such as female-typical interests and reproductive functioning [44]. A systematic review of the literature on hormonal transfer between co-twins concluded that, 'while uneven, the evidence for the [twin testosterone transfer] hypothesis is sufficient to warrant further investigation' (p. 713) [44]. The review found the most consistent evidence for hormonal transfer in studies investigating cognitive traits and hypothesized that inconsistencies across different traits may reflect differences in when certain phenotypes develop prenatally. Hence, these co-twin studies [44–46] have important limitations, as with any empirical research. However, these studies also align with earlier CAH studies [42,43] to provide converging evidence that prenatal androgens influence cognitive abilities. Scholars continue to debate this evidence and form differing conclusions [3,6,7].

Evidence for prenatal effects has been mixed in studies analyzing individual differences in androgen exposure. However, these mixed results may relate to methodological limitations, especially in the case of one widely used, but crude, indicator of androgen exposure based on individuals' finger lengths [43,48]. A few studies have analyzed more direct measures of prenatal androgen exposure (e.g., testosterone in amniotic fluid), but these measures are also limited [49]. For instance, in one recent study ($n = 64$), individual differences in amniotic testosterone predicted later performance on one spatial task (disembedding) but not others (mental rotation and targeting) [36]. These results are difficult to interpret because neural regions supporting specific spatial abilities and preferences develop during unknown gestational periods that may or may not coincide with the time of testosterone measurement [48,49].

Hence, barring correlational studies that have notable limitations [36,43,48], evidence from clinical [42,43] and nonclinical populations [44–46] indicates that prenatal androgens are likely to increase females' mental rotation performance and slightly decrease that of males (Box 2). Effects on any other cognitive abilities (spatial or otherwise) remain unclear, although current research is addressing this limitation [42,44,50]. Postnatal androgens may have smaller cognitive effects than prenatal androgens (Box 2) [51–63], consistent with androgen sensitivity decreasing during development [64,65].

Brain differences

Sex hormones encountered during critical developmental periods (e.g., *in utero*, shortly after birth, during puberty) are often assumed to have permanent, organizational effects on brain development, whereas sex hormones encountered during adulthood have temporary, activational effects on brain functioning [65]. However, distinctions between organizational and activational effects are often difficult to distinguish empirically, especially because environmental experiences continue to shape brain structure even in adulthood [66]. Recent data indicate nuanced interpretations of how prenatal androgens influence brain development. For instance, prenatal hormones could influence postnatal cognitive abilities, but indirectly through preferences [48]. Higher prenatal androgen exposure may cause females to seek out male-typical activities that are likely to enhance spatial cognition, according to mediational analyses in one recent CAH study ($n = 32$) [42]. Infant sex differences, regardless of whether robust [29,30] or not [31–35], also do not support interpretation of permanent brain differences caused by organizational hormonal effects. For instance, one recent study ($n = 293$) on neonates' brain structure concluded that androgens had 'some minor sex-specific effects...but did not appear to be the primary determinant of sexual dimorphism in this age group' (p. 9) [67]. In summary, the precise neural mechanisms that underlie the cognitive effects of prenatal androgens are unclear (Box 2), but current research offers promising research directions [42,45,67].

Longitudinal studies provide evidence that sex hormones influence some specific aspects of brain development during puberty. For instance, adolescents ($n = 284$) with higher androgen sensitivity showed more male-typical patterns of maturation in specific areas of the cerebral cortex [68]. This finding is potentially relevant to cognitive sex differences because the cerebral cortex, the outermost structure of the brain, supports most cognitive functioning. However, that study's authors cautioned that their dataset did not allow them to directly test brain–cognition relationships [68] and studies directly relating pubertal sex hormones to cognitive abilities have found mixed results [52,56,62]. Neural explanations of cognitive sex differences are complex, especially given findings that women and men sometimes use brain regions differently to achieve equal cognitive performance [69,70]. Recent research informs older theories about sex differences in brain lateralization (Box 2) [71–75] and newer theories about other neural characteristics such as proportions of white matter and connectivity between brain regions [70,76].

Cultural influences

Enormous international datasets (e.g., $n > 100{,}000$) have found large cross-cultural variation in cognitive sex differences. For instance, challenging the notion of universal male advantage in mathematics, sex differences in average mathematics test performance are not found in many nations and are even reversed (female advantage) in a few [16,77–79]. Female advantages in reading and male advantages in mental rotation are found in all nations analyzed so far (75 nations for reading, 53 for spatial) [16,23], but these sex differences vary in magnitude. For instance, male advantages in spatial (and mathematics) performance tend to be larger in wealthier nations [23,79] and in families with higher socioeconomic status within nations [28,80]. Female advantages in reading also vary substantially, but cross-national trends are unclear [16,79,81].

These cross-national findings have multiple plausible interpretations. For instance, boys could also learn spatial skills better or faster than girls, thus explaining why spatial sex differences are larger in nations with more educational resources [82]. However, meta-analytic findings provide evidence against this interpretation [83]. Another possibility relates to differential engagement in sex-typed activities [80,82]. For instance, some male-typical activities such as playing with construction toys or action video games can substantially improve spatial skills [83–85], even causing neural changes in cortical thickness [86] and sex-differentiated patterns of brain activation [69,86]. Ability and neural sex differences may therefore be larger in environments such as richer nations that provide more opportunities to engage in such sex-typed cognitive activities [80]. Other interpretations are also possible (Box 3).

Sex differences in mathematics test performance are also larger in nations with less gender equity (e.g., percentage of women among employed researchers) [77,79]. This literature's rapid development has understandably led to confusion over conceptualizations of core constructs such as gender equity. Contrasting with unidimensional operationalizations [16], Else-Quest and colleagues [77,87] argue that gender equity is a complex, multidimensional construct (Box 3). For instance, despite scoring highly on composite measures of gender equity, many Western European nations have large sex differences in the types of academic and occupational fields that men and women pursue [88,89]. Such sex segregation could then reinforce gender stereotypes even in 'gender-equal' nations such as The Netherlands [90]. Evidence suggests that gender equity in only some domains (e.g., education, workforce), and not others (e.g., health), may influence cognitive sex differences [77,79,91]. Hence, disagreement among scholars [16,78] may reflect differences in operationalizations of gender equity rather than differences in results. As discussed in Box 3, these cross-national findings build on socialization theories that focus on individual attitudinal constructs such as valuing of mathematics and intergenerational factors

Box 3. Defining gender equity

Gender equity refers to structural factors such as access to education and antidiscrimination policies that provide equal societal opportunities for women and men [87]. Else-Quest and colleagues argue that gender equity is multidimensional (e.g., equitable access to education weakly correlates with women's political agency) and that composite measures that collapse across multiple equity domains often do not pinpoint specific mechanisms [77,87].

Psychological theory should specify which equity domains are most relevant. For instance, according to theories of academic motivation [4,77], a girl may not persist in mathematics classes if she does not perceive their utility for the future (e.g., she observes that women are scarce in mathematics-intensive occupations). Girls' educational choices and mathematics test performance should therefore relate more strongly to women's employment in mathematics-intensive occupations specifically than all occupations generally. These predictions are supported in both cross-national research [77,79] and research conducted across school districts within the USA [91]. Also consistent with theoretical predictions, women's employment in the national research workforce predicted girls reporting more confidence in their mathematics ability, more motivation to pursue mathematical tasks, more valuing of mathematics, and less mathematics anxiety [77]. Previous longitudinal research provides evidence on how these multifaceted attitudinal constructs may influence academic choices and performance [4,5]. These cross-national findings extend previous research on socialization practices [4,5,8] by suggesting how broad sociocultural factors such as occupational sex segregation may influence individual-level outcomes such as valuing of mathematics [77]. Any strong causal interpretation of these data is limited because of their correlational nature, but the findings nevertheless demonstrate the need for psychological theories that can explain domain-specific, cross-national relationships [87].

Attesting to the multidimensionality of gender equity in general, sociologists distinguish between forms of occupational sex segregation that are vertical (men disproportionally have jobs with higher pay) and horizontal (the sexes have equal income, but different occupations) [89]. For instance, in Sweden women and men earn more-equal pay than in some other nations but pursue different types of occupations [88,89]. Factors other than cognitive sex differences are likely to contribute to cross-national variation in horizontal sex segregation. For instance, some sociologists have argued that economic prosperity increases such segregation for several reasons (e.g., diversification of occupational choices, stronger gender-essentialist ideologies) [88]. Once established, this segregation can enlarge cognitive sex differences as discussed [77,79] and reinforce stereotypes about women and men in specific academic fields (e.g., science) even in 'gender-equal' nations such as The Netherlands [90].

such as parental expectations [4,5]. Another socialization perspective that has received much recent attention regards the situational cognitive effects of gender stereotypes.

Gender stereotypes

Gender stereotypes may influence cognitive sex differences through a complex phenomenon known as stereotype threat (see Glossary) [92]. Stereotype-threat research builds on considerable previous literature on gender stereotypes [4,5,8,93] by experimentally establishing how they can have immediate situational effects on cognitive performance. For instance, reminding women of negative stereotypes about their mathematics abilities can immediately lower their mathematics test performance [92] and even cause differences in brain activation [94,95]. Some scholars debate this evidence [3], suggesting that these effects are not robust according to a meta-analysis [96]. Stereotype-threat researchers responded by arguing that the meta-analysis's selection criteria were biased and that a subsequent meta-analysis found robust effects [97]. Recent field research provides new evidence on stereotype-threat effects in real-world, applied settings. For instance, in a large, nationally representative sample ($n \sim 200{,}000$), experimental methods found evidence for small, but potentially important, stereotype-threat effects on a low-stakes, standardized mathematics exam [98]. Reducing stereotype threat increased some women's physics achievement over one college semester, illustrating how stereotype threat can have both immediate and longitudinal consequences [99]. Other studies [19,100,101] find analogous results, but much more field-based research is needed. Gender-stereotype research has also begun to investigate spatial [19,20,54,102,103] and verbal [104–106] cognitive tasks and has found encouraging but complex results. An exciting research direction investigates the role of teachers and parents in shaping stereotype threat [5]. For instance, girls (but not boys) in kindergarten underperformed and endorsed gender-mathematics stereotypes if their female teacher was anxious about mathematics [107], but were immune to stereotype-threat effects if their mothers rejected gender-mathematics stereotypes [108]. These studies and others [103,104,109] suggest that stereotype-threat effects may emerge as early as in kindergarten, although results are mixed [110]. In summary, both laboratory and field research suggest that stereotype threat may explain some, but not all, of the sex differences sometimes found in standardized test performance.

Biopsychosocial interactions

Based on the reviewed evidence, are biological or environmental influences more important in explaining cognitive sex differences? This question is flawed because it assumes a false dichotomy between biology and environment. As reviewed, biological factors such as prenatal androgens can influence how individuals select environments [42] and these environments can then cause further biological development [66,69,86]. Broad cultural factors such as gender equity can even reverse these sex differences in particular contexts and nations [77–79]. Biopsychosocial perspectives therefore describe biology and environment as two sets of intertwined factors that influence each other in a continuous causal loop (Figure 2) [1]. The reviewed evidence suggests that both sets of factors (e.g., prenatal androgens and gender stereotypes) fuel this intertwined loop to sometimes produce sex differences and sometimes sex similarities. Recent research has been increasingly using these broad perspectives [111] to test empirically specific biopsychosocial hypotheses in the context of cognitive sex differences [42,54,69,86,94,95]. These integrative approaches have potential for addressing other mysteries in this literature (Box 4). For instance, why do some cognitive tasks such as mental rotation show large sex differences but other closely related tasks such as mental folding do not [112]? Any theory of cognitive sex differences is incomplete if it cannot also explain why related tasks

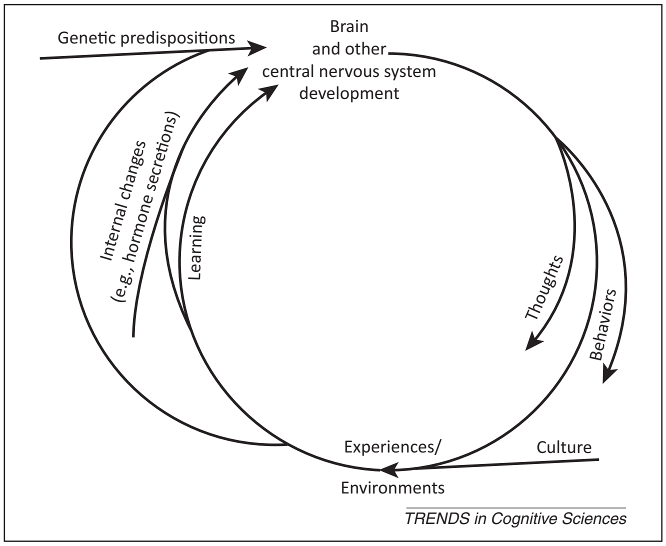

Figure 2. Biopsychosocial model. This model depicts how biology and environment exert reciprocal effects on each other. For instance, biological factors such as brain differences can affect how individuals select environments and these environmental factors can then cause further biological development. Both biology and culture (top-left and bottom-right arrows, respectively) serve as inputs that start this interacting causal loop, which sometimes produces sex differences and sometimes sex similarities. Reproduced, with permission, from [1].

show sex similarities [2]. Interdisciplinary theories and methods that integrate understanding of the brain, cognition, and culture are needed to help understand these complex findings.

Concluding remarks: societal implications

What implications do these cognitive sex differences have? Importantly, these findings describe group averages and therefore often have limited relevance to understanding individual men and women [2]. Many men excel in writing tasks and many women excel in mental rotation tasks, even if group averages exist. Do these group averages, however, explain other group averages such as the underrepresentation of women in science and engineering fields [3,113]? Some research suggests 'partly', but for non-obvious reasons. For instance, among individuals with high mathematics test performance, individuals with higher verbal performance are less likely to pursue science and engineering fields [114,115]. These results suggest that individuals' relative cognitive strengths are important to educational and career decisions. This finding may be relevant because, on average, men are more likely than women to have profiles of high mathematics but moderate verbal test performance [114,115]. However, other factors may play a more central role in explaining such career choices, such as work–family balance, which is more difficult for women who traditionally do the work of care-giving [3], or perceptions that certain occupations do not afford communal goals (e.g., working with or helping other people), which women endorse more strongly than men [116].

This literature offers insight on how educational policies and well-designed curricula can maximize women's and men's cognitive potential. For instance, some scholars have suggested that single-sex education might benefit some boys and girls by tailoring instruction to their learning needs [117]. However, the data indicate no clear academic advantage for single-sex or mixed-sex schools [117,118] and the potential benefits and harms of single-sex education are debated on other grounds [117,119]. Fortunately, other educational research indicates clearer findings. Well-designed curricula can improve cognitive abilities and educational outcomes for both sexes [83–85,120], even resulting in changes in brain function and structure [66,86]. Removing stereotype threat can improve both men's [104] and women's [99] academic achievement. As interdisciplinary approaches emerge to understand sex differences and similarities, researchers need to also consider these pressing societal implications.

Box 4. Outstanding questions

- How do prenatal sex hormones influence cognitive ability-related brain development directly *in utero* and indirectly through activity preferences after birth?
- How does the brain's sensitivity to sex hormones change *in utero* and during puberty, especially in neural regions supporting cognitive abilities and preferences?
- How do longitudinal changes in brain development bidirectionally relate to differences in environmental experiences and cognitive abilities?
- What explains cross-temporal and cross-national variation in cognitive sex differences, especially in the domain of reading and writing?
- When do stereotype-threat effects emerge in development and how do parents, teachers, and peers cause or protect against these effects?
- How do gender stereotypes influence sex differences in spatial and verbal tasks?
- How can literature on cognitive sex differences be optimally used to maximize women's and men's cognitive potential?

Acknowledgments

This review is based on work supported by the National Science Foundation Graduate Research Fellowship (Grant No. DGE-0824162) awarded to D.I.M. The authors thank Andrea Frick for comments on an earlier version of this manuscript.

References

1 Halpern, D.F. (2012) *Sex Differences in Cognitive Abilities*. (4th edn), Psychology Press
2 Hyde, J.S. (2005) The gender similarities hypothesis. *Am. Psychol.* 60, 581–592
3 Ceci, S.J. *et al.* (2009) Women's underrepresentation in science: sociocultural and biological considerations. *Psychol. Bull.* 135, 218–261
4 Eccles, J.S. (2007) Where are all the women? Gender differences in participation in physical science and engineering. In *Why Aren't More Women in Science? Top Researchers Debate the Evidence* (Ceci, S.J. and Williams, W.M., eds), pp. 199–210, American Psychological Association
5 Gunderson, E.A. *et al.* (2012) The role of parents and teachers in the development of gender-related math attitudes. *Sex Roles* 66, 153–166
6 Hines, M. (2010) Sex-related variation in human behavior and the brain. *Trends Cogn. Sci.* 14, 448–456
7 Jordan-Young, R.M. (2010) *Brain Storm: The Flaws in the Science of Sex Differences*, Harvard University Press
8 Arthur, A.E. *et al.* (2008) Gender stereotyping and prejudice in young children: a developmental intergroup perspective. In *Intergroup Attitudes and Relations in Childhood through Adulthood* (Levy, S.R. and Killen, M., eds), pp. 66–86, Oxford University Press
9 Wai, J. *et al.* (2010) Sex differences in the right tail of cognitive abilities: a 30 year examination. *Intelligence* 38, 412–423

10 Lakin, J.M. (2013) Sex differences in reasoning abilities: surprising evidence that male-female ratios in the tails of the quantitative reasoning distribution have increased. *Intelligence* 41, 263–274
11 Hedges, L.V. and Nowell, A. (1995) Sex differences in mental test scores, variability, and numbers of high-scoring individuals. *Science* 269, 41–45
12 Hyde, J.S. *et al.* (1990) Gender differences in mathematics performance: a meta-analysis. *Psychol. Bull.* 107, 139–155
13 Lindberg, S.M. *et al.* (2010) New trends in gender and mathematics performance: a meta-analysis. *Psychol. Bull.* 136, 1123–1135
14 Hill, C. *et al.* (2010) *Why So Few? Women in Science, Technology, Engineering, and Mathematics.* American Association of University of Women
15 Hyde, J.S. and Linn, M.C. (1988) Gender differences in verbal ability: a meta-analysis. *Psychol. Bull.* 104, 53–69
16 Stoet, G. and Geary, D.C. (2013) Sex differences in mathematics and reading achievement are inversely related: within- and across-nation assessment of 10 years of PISA data. *PLoS ONE* 8, e57988
17 Christie, G.J. *et al.* (2013) Mental rotational ability is correlated with spatial but not verbal working memory performance and P300 amplitude in males. *PLoS ONE* 8, e57390
18 Herlitz, A. and Lovén, J. (2013) Sex differences and the own-gender bias in face recognition: A meta-analytic review. *Vis. Cogn.* http://dx.doi.org/10.1080/13506285.2013.823140
19 Huguet, P. and Régner, I. (2007) Stereotype threat among schoolgirls in quasi-ordinary classroom circumstances. *J. Educ. Psychol.* 99, 545–560
20 Huguet, P. and Régner, I. (2009) Counter-stereotypic beliefs in math do not protect school girls from stereotype threat. *J. Exp. Soc. Psychol.* 45, 1024–1027
21 Kaufman, S.B. (2007) Sex differences in mental rotation and spatial visualization ability: can they be accounted for by differences in working memory capacity? *Intelligence* 35, 211–223
22 Voyer, D. *et al.* (2007) Gender differences in object location memory: a meta-analysis. *Psychon. Bull. Rev.* 14, 23–38
23 Lippa, R.A. *et al.* (2010) Sex differences in mental rotation and line angle judgments are positively associated with gender equality and economic development across 53 nations. *Arch. Sex. Behav.* 39, 990–997
24 Peters, M. *et al.* (1995) A redrawn Vandenburg and Kuse Mental Rotations Test: different versions and factors that affect performance. *Brain Cogn.* 28, 39–58
25 Voyer, D. (2011) Time limits and gender differences on paper-and-pencil tests of mental rotation: a meta-analysis. *Psychon. Bull. Rev.* 18, 267–277
26 Voyer, D. *et al.* (1995) Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychol. Bull.* 117, 250–270
27 Robinson, J.P. and Lubienski, S.T. (2011) The development of gender achievement gaps in mathematics and reading during elementary and middle school: examining direct cognitive assessments and teacher ratings. *Am. Educ. Res. J.* 48, 268–302
28 Penner, A.M. and Paret, M. (2008) Gender differences in mathematics achievement: exploring the early grades and the extremes. *Soc. Sci. Res.* 37, 239–253
29 Moore, D.S. and Johnson, S.P. (2011) Mental rotation of dynamic, three-dimensional stimuli by 3-month-old infants. *Infancy* 16, 435–445
30 Quinn, P.C. and Liben, L.S. (2013) A sex difference in mental rotation in infants: Convergent evidence. *Infancy* http://dx.doi.org/10.1111/infa.12033
31 Frick, A. and Möhring, W. (2013) Mental object rotation and motor development in 8- and 10-month infants. *J. Exp. Child Psychol.* 115, 708–720
32 Frick, A. and Wang, S. (2013) Mental spatial transformations in 14- and 16-month infants: effects of action and observational experience. *Child Dev.* http://dx.doi.org/10.1111/cdev.12116
33 Möhring, W. and Frick, A. (2013) Touching up mental rotation: effects of manual experience on 6-month-old infants' mental object rotation. *Child Dev.* 84, 1554–1565
34 Schwarzer, G. *et al.* (2013) Crawling is associated with mental rotation ability by 9-month-old infants. *Infancy* 18, 432–441
35 Schwarzer, G. *et al.* (2013) How crawling and manual object exploration are related to the mental rotation abilities of 9-month-old infants. *Front. Psychol.* 4, 97
36 Auyeung, B. *et al.* (2012) Effects of fetal testosterone on visuospatial ability. *Arch. Sex. Behav.* 41, 571–581
37 Hahn, N. *et al.* (2010) Preschoolers' mental rotation: sex differences in hemispheric asymmetry. *Cogn. Neurosci.* 22, 1244–1250
38 Jansen, P. *et al.* (2013) Mental rotation performance in primary school age children: are there gender differences in chronometric tests? *Cogn. Dev.* 28, 51–62
39 Frick, A. *et al.* (2013) Development of mental rotation in 3- to 5-year-old children. *Cogn. Dev.* 28, 386–399
40 Gunderson, E.A. *et al.* (2013) Teachers' spatial anxiety relates to 1st- and 2nd-graders' spatial learning. *Mind Brain Educ.* 7, 196–199
41 Ramirez, G. *et al.* (2012) Spatial anxiety relates to spatial abilities as a function of working memory in children. *Q. J. Exp. Psychol.* 65, 474–487
42 Berenbaum, S.A. *et al.* (2012) Early androgen effects on spatial and mechanical abilities: evidence from congenital adrenal hyperplasia. *Behav. Neurosci.* 126, 86–96
43 Puts, D.A. *et al.* (2008) Spatial ability and prenatal androgens: meta-analyses of congenital adrenal hyperplasia and digit ratio (2D:4D) studies. *Arch. Sex. Behav.* 37, 100–111
44 Tapp, A.L. *et al.* (2011) Evaluating the twin testosterone transfer hypothesis: a review of the empirical evidence. *Horm. Behav.* 60, 713–722
45 Heil, M. *et al.* (2011) Mental rotation in female fraternal twins: evidence for intra-uterine hormone transfer? *Biol. Psychol.* 86, 90–93
46 Vuoksimaa, E. *et al.* (2010) Having a male co-twin masculinizes mental rotation performance in females. *Psychol. Sci.* 21, 1069–1071
47 Ribeiro, D.C. *et al.* (2013) Intrauterine hormone effects on tooth dimensions. *J. Dent. Res.* 92, 425–431
48 Valla, J.M. and Ceci, S.J. (2011) Can sex differences in science be tied to the long reach of prenatal hormones? Brain organization theory, digit ratio (2D/4D), and sex differences in preferences and cognition. *Perspect. Psychol. Sci.* 6, 134–146
49 Constantinescu, M. and Hines, M. (2012) Relating prenatal testosterone exposure to postnatal behavior in typically developing children: methods and findings. *Child Dev. Perspect.* 6, 407–413
50 Whitehouse, A.J.O. *et al.* (2010) Fetal androgen exposure and pragmatic language ability of girls in middle childhood: implications for the extreme male-brain theory of autism. *Psychoneuroendocrinology* 35, 1259–1264
51 Courvoisier, D.S. *et al.* (2013) Sex hormones and mental rotation: an intensive longitudinal investigation. *Horm. Behav.* 63, 345–351
52 Durdiaková, J. *et al.* (2013) Mental rotation in intellectually gifted boys is affected by the androgen receptor CAG repeat polymorphism. *Neuropsychologia* 51, 1693–1698
53 Griksiene, R. and Ruksenas, O. (2011) Effects of hormonal contraceptives on mental rotation and verbal fluency. *Psychoneuroendocrinology* 36, 1239–1248
54 Hausmann, M. *et al.* (2009) Interactive effects of sex hormones and gender stereotypes on cognitive sex differences – a psychobiosocial approach. *Psychoneuroendocrinology* 34, 389–401
55 Henderson, V.W. and Popat, R.A. (2011) Effects of endogenous and exogenous estrogen exposures in midlife and late-life women on episodic memory and executive functions. *Neuroscience* 191, 129–138
56 Herlitz, A. *et al.* (2013) Cognitive sex differences are not magnified as a function of age, sex hormones, or puberty development during early adolescence. *Dev. Neuropsychol.* 38, 167–179
57 Kocoska-Maras, L. *et al.* (2011) A randomized trial of the effect of testosterone and estrogen on verbal fluency, verbal memory, and spatial ability in healthy postmenopausal women. *Fertil. Steril.* 95, 152–157
58 Matousek, R.H. and Sherwin, B.B. (2010) Sex steroid hormones and cognitive functioning in healthy, older men. *Horm. Behav.* 57, 352–359
59 Ostatníková, D. *et al.* (2010) Spatial abilities during the circalunar cycle in both sexes. *Learn. Individ. Differ.* 20, 484–487
60 Puts, D.A. *et al.* (2010) Salivary testosterone does not predict mental rotation performance in men or women. *Horm. Behav.* 58, 282–289

61 Thilers, P.P. *et al.* (2006) The association between endogenous free testosterone and cognitive performance: a population-based study in 35 to 90 year-old men and women. *Psychoneuroendocrinology* 31, 565–576
62 Vuoksimaa, E. *et al.* (2012) Pubertal testosterone predicts mental rotation performance of young adult males. *Psychoneuroendocrinology* 37, 1791–1800
63 Yonker, J.E. *et al.* (2006) Negative association of testosterone on spatial visualization in 35 to 80 year old men. *Cortex* 42, 376–386
64 Beltz, A.M. and Berenbaum, S.A. (2013) Cognitive effects of variations in pubertal timing: is puberty a period of brain organization for human sex-typed cognition? *Horm. Behav.* 63, 823–828
65 Schulz, K.M. *et al.* (2009) Back to the future: the organizational–activational hypothesis adapted to puberty and adolescence. *Horm. Behav.* 55, 597–604
66 May, A. (2011) Experience-dependent structural plasticity in the adult human brain. *Trends Cogn. Sci.* 15, 475–482
67 Knickmeyer, R.C. *et al.* (2013) Impact of sex and gonadal steroids on neonatal brain structure. *Cereb. Cortex* http://dx.doi.org/10.1093/cercor/bht125
68 Raznahan, A. *et al.* (2010) Longitudinally mapping the influence of sex and androgen signaling on the dynamics of human cortical maturation. *Proc. Natl. Acad. Sci. U.S.A.* 107, 16988–16993
69 Jaušovec, N. and Jaušovec, K. (2012) Sex differences in mental rotation and cortical activation patterns: can training change them? *Intelligence* 40, 151–162
70 Lenroot, R.K. and Giedd, J.N. (2010) Sex differences in the adolescent brain. *Brain Cogn.* 72, 48–55
71 Pfannkuche, K.A. *et al.* (2009) Does testosterone affect lateralization of brain and behavior? A meta-analysis in humans and other animal species. *Philos. Trans. R. Soc. B: Biol. Sci.* 364, 929–942
72 Sommer, I.E. *et al.* (2008) Sex differences in handedness, asymmetry of the planum temporale and functional language lateralization. *Brain Res.* 1206, 76–88
73 Vogel, J.J. *et al.* (2003) Cerebral lateralization of spatial abilities: a meta-analysis. *Brain Cogn.* 52, 197–204
74 Voyer, D. (2011) Sex differences in dichotic listening. *Brain Cogn.* 76, 245–255
75 Voyer, D. and Doyle, R.A. (2012) Response format, magnitude of laterality effects and sex differences in laterality. *Laterality* 17, 259–274
76 Peper, J.S. *et al.* (2011) Sex steroid and connectivity in the human brain: a review of neuroimaging studies. *Psychoneuroendocrinology* 36, 1101–1113
77 Else-Quest, N.M. *et al.* (2010) Cross-national patterns of gender differences in mathematics: a meta-analysis. *Psychol. Bull.* 136, 103–127
78 Kane, J.M. and Mertz, J.E. (2012) Debunking myths about gender and mathematics performance. *Notices AMS* 59, 10–21
79 Reilly, D. (2012) Gender, culture, and sex-typed cognitive abilities. *PLoS ONE* 7, e39904
80 Levine, S.C. *et al.* (2005) Socioeconomic status modifies the sex differences in spatial skill. *Psychol. Sci.* 16, 841–845
81 Marks, G.N. (2008) Accounting for the gender gaps in student performance in reading and mathematics: evidence from 31 countries. *Oxford Rev. Educ.* 34, 89–109
82 Ceci, S.J. and Papierno, P.B. (2005) The rhetoric and reality of gap closing: when the "have-nots" gain but the "haves" gain more. *Am. Psychol.* 60, 149–160
83 Uttal, D.H. *et al.* (2013) The malleability of spatial skills: a meta-analysis of training studies. *Psychol. Bull.* 139, 352–402
84 Uttal, D.H. *et al.* (2013) Exploring and enhancing spatial thinking: links to achievement in science, technology, engineering, and mathematics? *Curr. Dir. Psychol. Sci.* 22, 367–373
85 Miller, D.I. and Halpern, D.F. (2013) Can spatial training improve long-term outcomes for gifted STEM undergraduates? *Learn. Individ. Differ.* 26, 141–152
86 Haier, R.J. *et al.* (2009) MRI assessment of cortical thickness and functional activity changes in adolescent girls following three months of practice on a visual–spatial task. *BMC Res. Notes* 2, 174
87 Else-Quest, N.M. and Grabe, S. (2012) The political is personal: measurement and application of national-level indicators of gender equity in psychological research. *Psychol. Women Q.* 36, 131–144
88 Charles, M. and Bradley, K. (2009) Indulging our gendered selves? Sex segregation by field of study in 44 countries. *Am. J. Sociol.* 114, 924–976
89 Jarman, J. *et al.* (2012) The dimensions of occupational gender segregation in industrial countries. *Sociology* 46, 1003–1019
90 Nosek, B.A. *et al.* (2009) National differences in gender-science stereotypes predict national sex differences in science and math achievement. *Proc. Natl. Acad. Sci. U.S.A.* 106, 10593–10597
91 Riegle-Crumb, C. and Moore, C. (2013) The gender gap in high school physics: considering the context of local communities. *Soc. Sci. Q.* http://dx.doi.org/10.1111/ssqu.12022
92 Schmader, T. (2010) Stereotype threat deconstructed. *Curr. Dir. Psychol. Sci.* 19, 14–18
93 Nosek, B.A. and Smyth, F.L. (2011) Implicit social cognitions predict sex differences in math engagement and achievement. *Am. Educ. Res. J.* 48, 1125–1156
94 Derks, B. *et al.* (2013) Sex differences in neural efficiency: are they due to stereotype threat effect? *Pers. Individ. Differ.* 55, 744–749
95 Krendl, A.C. *et al.* (2008) The negative consequences of threat: a functional magnetic resonance imaging investigation of the neural mechanisms underlying women's underperformance in math. *Psychol. Sci.* 19, 168–175
96 Stoet, G. and Geary, D.C. (2012) Can stereotype threat explain the gender gap in mathematics performance and achievement. *Rev. Gen. Psychol.* 16, 93–102
97 Picho, K. *et al.* (2013) Exploring the moderating role of context on the mathematics performance of females under stereotype threat: a meta-analysis. *J. Soc. Psychol.* 153, 299–333
98 Wei, T.E. (2012) Sticks, stones, words, and broken bones: new field and lab evidence on stereotype threat. *Educ. Eval. Policy Anal.* 34, 465–488
99 Miyake, A. *et al.* (2010) Reducing the gender achievement gap in college science: a classroom study of values affirmation. *Science* 330, 1234–1237
100 Smeding, A. *et al.* (2013) Order of administration of math and verbal tests: an ecological intervention to reduce stereotype threat on girls' math performance. *J. Educ. Psychol.* 105, 850–860
101 Walton, G.M. and Spencer, S.J. (2009) Latent ability: grades and test scores systematically underestimate the intellectual ability of negatively stereotyped students. *Psychol. Sci.* 20, 1132–1139
102 Moè, A. (2012) Gender difference does not mean genetic difference: externalizing improves performance in mental rotation. *Learn. Individ. Differ.* 22, 20–24
103 Neuburger, S. *et al.* (2012) A threat in the classroom: gender stereotype activation and mental-rotation performance in elementary-school children. *Z. Psychol.* 220, 61–69
104 Hartley, B.L. and Sutton, R.M. (2013) A stereotype threat account of boys' academic underachievement. *Child Dev.* 84, 1716–1733
105 Hirnstein, M. *et al.* (2012) Gender stereotyping enhancing verbal fluency performance in men (and women). *Z. Psychol.* 220, 70–77
106 Shih, M. *et al.* (2006) Domain-specific effects of stereotypes on performance. *Self Identity* 5, 1–14
107 Beilock, S.L. *et al.* (2010) Female teachers' math anxiety affects girls' math achievement. *Proc. Natl. Acad. Sci. U.S.A.* 107, 1860–1863
108 Tomasetto, C. *et al.* (2011) Girls' math performance under stereotype threat: the moderating role of mothers' gender stereotypes. *Dev. Psychol.* 47, 943–949
109 Galdi, S. *et al.* (2013) The roots of stereotype threat: when automatic associations disrupt girls' math performance. *Child Dev.* http://dx.doi.org/10.1111/cdev.12128
110 Ganley, C.M. *et al.* (2013) An examination of stereotype threat effects on girls' mathematics performance. *Dev. Psychol.* 49, 1886–1897
111 Eagly, A.H. and Wood, W. (2013) The nature-nurture debates: 25 years of challenges in understanding the psychology of gender. *Perspect. Psychol. Sci.* 8, 340–357
112 Harris, J. *et al.* (2013) Understanding spatial transformations: similarities and differences between mental rotation and mental folding. *Cogn. Process.* 14, 105–115
113 Wai, J. *et al.* (2009) Spatial ability for STEM domains: aligning over 50 years of cumulative psychological knowledge solidifies its importance. *J. Educ. Psychol.* 101, 817–835
114 Park, G. *et al.* (2007) Contrasting intellectual patterns predict creativity in the arts and sciences. *Psychol. Sci.* 18, 948–952

115 Wang, M.T. *et al.* (2013) Not lack of ability but more choice: individual and gender differences in choice of careers in science, technology, engineering, and mathematics. *Psychol. Sci.* 24, 770–775
116 Diekman, A.B. *et al.* (2011) Malleability in communal goals and beliefs influences attraction to STEM careers: evidence for a goal congruity perspective. *J. Pers. Soc. Psychol.* 101, 902–918
117 Mael, F. *et al.* (2005) *Single-sex versus Coeducational Schooling: A Systematic Review*, US Department of Education
118 Pahlke, E. *et al.* (2013) The effects of single-sex compared with coeducational schooling on mathematics and science achievement: data from Korea. *J. Educ. Psychol.* 105, 444–452
119 Halpern, D.F. *et al.* (2011) The pseudoscience of single-sex schooling. *Science* 333, 1706–1707
120 Stieff, M. *et al.* (2013) Strategy training eliminates sex differences in spatial problem solving in a STEM domain. *J. Educ. Psychol.* (in press)