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A biopsychological–social view of mathematical development

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The biological, social, and individual-level foundations of mathematics development are typically studied in isolation. However, isolated study of these areas can only offer limited understanding. In order to facilitate a holistic, integrative view of the field, here, we review recent studies in several of the above domains, focusing on how individual-level cognitive, emotional, motivational, and self-concept-related variables interact within- and cross-domain.

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We summarize our view in Figure 1. In this succinct overview, we cannot cover all potentially important variables in detail. Our focus is on organizing particularly important variables integrated by a large-scale view while pointing to recent developments regarding some major questions. Notably, temporal change is inherent to developmental views. In addition, the demands of age-appropriate mathematics are also continuously increasing, and the focus of instruction is changing. So, crucial factors and their connections can substantially evolve during development. While we acknowledge that considering different levels of analysis is challenging, we believe that the integrative approach outlined here could greatly enhance research efforts toward a comprehensive understanding of math development.

Biological factors

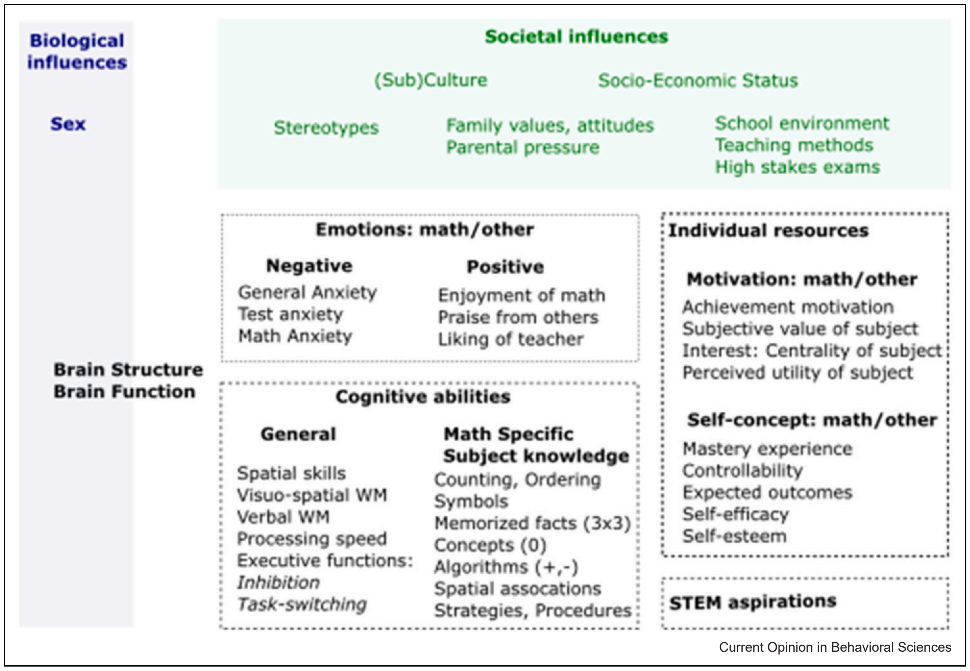
Several studies explored the role of genetic and environmental etiology of mathematical abilities, difficulties, and mathematics anxiety (MA). Cognitive abilities have been studied most systematically from a multivariate genetic perspective. This research has consistently showed that the phenotypic correlations among cognitive abilities are mediated by genetic factors called generalist genes [78]. Twin studies comparing phenotypic (observed) similarity between monozygotic and dizygotic twins [54,83] found moderate heritability estimates (from .30 to .45) across different mathematics domains [53,112]. A study has analyzed data from more than 1400 twin pairs and found that the heritability of general, spatial, and math anxiety ranged from 30% to 41%. Another study assessed more than 5000 twin pairs of 12-year-old twins and showed that genetic factors consistently accounted for more than half of the phenotypic correlations among intelligence, reading mathematics, and language [26]. Potential biological sex differences are of continued interest, especially in relation to potential differences in spatial skills [38,39].

Many studies aim to discover brain correlates of educational phenomena and they often offer (implicit) causal explanations. An important caveat to remember is that finding some brain marker of achievement does not imply that the brain marker is the cause of achievement. The brain marker may just as well be the consequence of some environmental influence (e.g. lack of appropriate teaching) that led to the measured achievement. Put otherwise, it is *obvious* that environmental inputs must cause an impact on brain function. Had they not influenced brain function, they could not influence behavior. Clearly, if no other supporting evidence is available than it, it is incorrect to unequivocally interpret brain-based variables as causal factors behind behavior.

Cognitive abilities

Mathematics is a complex subject, comprising multiple areas of expertise. Both math-specific knowledge and domain-general cognitive skills are possible sources of individual differences in math achievement. Regarding math-specific knowledge, a key question is whether measures of *mental representations* (latent concepts) would correlate with math performance. Notably, simply

Figure 1



An integrative view of math development. Genetic (blue background) and social (green) factors interact with individual-level variables (white). Many, not necessarily strictly hierarchically organized (causal) connections are possible between these factors. The presence of factors and their connections can change through developmental time. Brain structure and function are influenced by genetic control but experience (e.g. teaching) also shapes brain structure and function (hence the mixed, blue/white background). The list of factors and abilities here is not exhaustive.

finding correlations between tasks and math achievement may not tell us much about the underlying representations. For example, symbolic number comparison accuracy often correlates with early school math achievement or predicts it [17,44]. However, such comparison ability is an expected outcome of primary school learning. Hence, measuring comparison accuracy directly tests a school-relevant skill [104] rather than being a test of a latent construct associated with school-relevant skills [69]. In contrast, a putative measure of underlying representations, the numerical distance effect has negligible correlations with math achievement [17]. Overall, training studies have rarely demonstrated far-transfer effects [85,86]. Nevertheless, a recent study reported that spatial training may enhance math [51].

Regarding domain-general cognitive skills, interest is revived in the classically often-assumed connection between space and number [65]. Visuospatial working memory (WM) may provide a mental workspace for some aspects of mathematical thinking [17,68]. It is a question whether spatial thinking can be distinguished from general intelligence [43] and if so, whether it consists of multiple subdomains (e.g. spatial visualization, form perception, and an ability to manipulate spatial scales [65]), or whether visuospatial WM can be considered a unique factor at all [65]. Further questions concern whether verbal and visuospatial WM [1,111,59], intelligence, and spatial skills [90] relate to different kinds of math measures, distinguish children with different math achievement profiles [87,90], and whether there are significant gender differences (note that consistently with the relevant literature, here 'gender' refers to biological sex) in spatial skills [38,39,68]. Similar questions can be raised about executive functions, particularly inhibition and task-switching skills [107,22,13].

Building links between space and (negative) numbers seems a gradual learning process [19,66]. A strong (automatic) account of number-space integration is unlikely to be true: a 1300-participant multilab replication study failed to replicate the claim that the mere presentation of numbers elicits spatial associations and found practically zero effect sizes across a range of analyses considering various potential moderating variables [20].

Recent data suggest that a popular concept, the Approximate Number System (ANS), has negligible ($r \approx 0.1$) relation to primary school mathematics outcomes [17,41], ANS training does not lead to the improvement of symbolic math skills [98,104], and symbolic math skills may sharpen the ANS rather than the other way round [56]. Subitizing (quick enumeration) is also unrelated to math abilities [3]. These findings question the construct validity of putative core math domain-specific concepts. The failure to find strong ANS versus math achievement correlations [17] and the failure to replicate ANS training effects [98] question the construct validity of the core element of the so-called triple-code model of math competence, at least for developmental populations. Further findings could also be flagged for replication, and especially neuroimaging studies should aim to substantially increase their sample size to produce more precise results [102].

A key practical question is whether specific cognitive predictors of mathematical achievement and development can be identified and implicated in the etiology of specific mathematics learning difficulties (MLD), and whether training predictors could boost mathematics achievement in MLD and other children. Notably, research on gifted or talented mathematics development is still rudimentary [64,67].

Recent studies suggest that children with MLD show spatial and visual WM deficits rather than ANS deficits [77,100]. Taking a multidimensional, distributional approach to studying MLD [99] led to the conclusion that it is unlikely that MLD is based on some cognitive core deficit [63]. Heterogeneous MLD profiles may be due to varied weaknesses in strongly overlapping WM/executive function constructs [99] related to individual differences rather than core deficits. Diagnostic precision of MLD needs to improve: thresholds vary between 1% and 15% [30] and even WM measures have poor diagnostic power on their own [63]. Cognitive diagnostic measures may be more efficient if multiple measurement dimensions are considered simultaneously.

Negative and positive emotions

MA is anxiety about learning and doing mathematics. MA likely affects student well-being and mental health, the liking of mathematics, and whether students orient themselves toward mathematics-related career choices, typically science, technology, engineering, and mathematics (STEM) careers [4]. At sample level, MA is one of the most robust negative correlates of math achievement from early primary school [7,18], with a highly replicable effect size ($r \approx -0.3$). MA strongly ($r \approx 0.6$–0.7) correlates with test anxiety but is separable from it [18]. Also, MA may be ‘the typical’ anxiety students may think of when their test anxiety is measured.

Importantly, most students with high MA are medium-to-high achievers ad MLD and MA strongly dissociate [31]. The MA-achievement correlation also exists at the country level [70]. However, Shanghai and other Asian locations are notable exceptions with very high MA relative to their achievement level ([70], p102). Females have notably higher MA than males in most countries [70] even when there is no gender gap in performance [29,31,47]. Hence, while MA and achievement can mutually affect each other [6,14,36], low achievement is not a necessary cause or consequence of MA (see later).

While MA seems less separable from general anxiety in primary school, it develops an increasingly specific relation with academic achievement by secondary school [15,18,47]. Perhaps, genetically grounded [61] high general anxiety levels may represent one particular risk factor in developing high MA [15].

Most recent studies focused on negative emotions in the context of mathematics learning, especially MA. However, education researchers have emphasized the significance of positive affective factors and emotions in influencing variations in students’ levels of motivation and academic achievement [10,60,91]: emotions and performance in mathematics can be interconnected through virtuous cycles, involving positive emotions, and vicious cycles, involving negative emotions, over time [75].

By considering not only negative emotions, but also specific emotions such as enjoyment, or motivational constructs such as situational and individual interest, we can generate more comprehensive insights into the affect of both students and teachers [89].

Self-determination theory addresses emotional experiences resulting from need satisfaction [84]. The theory assumes that people strive to experience themselves as competent, to act autonomously, and to relate to other persons socially. The attainment of these needs is accompanied by positive emotional experiences. Flow theory specifically focuses on optimal subjective experience [23]. Both the above theories are relevant, especially for the high math achievement range.

Cognitive and emotional factors independently affect achievement and math career choices [31]. The complex causal connections between factors may be difficult to disentangle and may show substantial individual variability [103]. Recent findings suggest that spatial ability, in-class attention, and MA would be particularly important predictors of adolescents’ math achievement [40] and that stronger visuospatial skills may be able to compensate for worse attentive behavior in boys [39]. High MA seems to link with online (visual) memory capacity [5,24,47,76,117].

The interconnected nature of cognitive variables and emotions calls for intervention methods tailored to individual children’s needs [103]. Low-performing students may benefit from math training boosting confidence [73], some boys may benefit from attention training [39], and better-performing students with high

MA may benefit from learning to separate MA from math performance, from boosting their ego-resiliency [32], reducing or regulating worries [72] and physiological components of MA [12], or seeing math tasks as a challenge instead of a threat to avoid [49]. Girls may particularly benefit from understanding gendered social attitudes toward math and STEM fields [103].

Individual resources: motivation, values, costs, and self-concept

Individual resources are attributes that help individuals to foster competence and sustain successful development in different functional domains (e.g. individual, school, and family) [27]. Individual factors such as self-concept, self-efficacy, self-esteem, and motivation may play important roles in math achievement and could act as protective factors against failure. For example, interview data suggest that low and high MA individuals' school experiences are similar but subjective interpretations of experiences differ [16]. Some important factors shaping experiences are mathematical self-efficacy [70,116], self-concept [50], and the subjective value of mathematics [55]. All of these factors are influenced by family and school-related variables during many years. For example, girls show lower mathematical self-efficacy then boys for the same level of math performance [116] and self-efficacy perceptions may drive the gender gap in pay [94].

Regarding motivation, facilitating and debilitating effects of MA on math performance vary not only across different levels of MA, but also as a function of how motivated children are to perform well [112]. A study of more than 900 children identified eight distinct profiles characterized by various combinations of dimensions of MA and math-motivation [113]. These findings do not agree with the idea that high MA students have low motivation. Specifically, highly motivated students were still likely to experience test MA, but they were less likely to experience learning MA. Girls were more likely to be characterized by a combination of lower math-motivation and higher MA compared with boys, revealing the complexity in the math-specific emotion-motivation relation beyond a single negative correlation. Other studies highlighted the importance of self-concept and resilience in relation to different levels of anxiety risk profiles [62] and found that both WM and self-concept mediated the relation between MA and math achievement in primary school children [52].

Expectancy-value theory [34] assumes that educational choices, and ultimately achievement, are influenced by two sets of beliefs: expectations of success and subjective task value. Expectancies for success are stronger predictors of actual academic achievement [34], whereas value beliefs are stronger predictors of engagement and academic career choices [115]. The complementary control-value theory further emphasizes the importance of control over mathematics activities [74]. The subjective value attached to mathematics and expectations about success, failure, and control can clearly drive student behavior [58,79,80]. However, it is also important to consider that academic and nonacademic self-esteem can be dissociated from each other [28]. Academically weak students may devalue school-related activities to protect their overall self-worth [2,79]. Socially disadvantaged students may also devalue school-related activities as these may be associated with high effort, emotional, opportunity, or monetary costs (e.g. the prospective price of college education in the USA, or the number of years spent studying rather than earning money) [35,46]. Such devaluation may especially affect mathematics that is often perceived as a difficult subject. In contrast, some students may be motivated by the high-utility value of math (helps to get a good job) and by the high social approval (e.g. from parents) associated with math. Hence, studies should increasingly investigate how perceived positive values and costs of school subjects, motivations, and aspirations interact [35].

Social factors: parents, teachers, school, and society

Mathematical learning difficulties, while known to have a genetic or hereditary component, typically manifest as a complex interplay of environmental and neurodevelopmental factors within instructional and sociocultural context [81]. The potential transfer of math-related attitudes and especially MA, from parents to their children, has received a lot of recent attention with positive [8,57] and negative [21] results in preschool children. Further, an important general variable affecting both school and parental environment, self-perceptions, and career aspirations is socioeconomic status (SES), a strong correlate of math literacy [48]. The amount of parental number talk positively correlated with SES and negatively with parental MA [9]. In school age children, MA was related to mothers' but not fathers' MA in grade 6, but this relationship was marginal once both parents' educational level was considered [110]. Others reported that fathers' and mothers' MA had differential importance in grades 1 and 3 [97].

The home math environment, encompassing all math-related interactions between parents and children at home, such as informal board game playing, parents' expressions of their math-related attitudes, beliefs, and expectations, has garnered significant attention in recent years. However, the results of a recent meta-analysis [25] detected a small and positive correlation (r = .13) with mathematics achievement. Hence, the impact of the home math environment over children's math achievement is consistent but minimal.

Regarding teachers' influence, classical findings indicated high MA in trainee US math teachers [45]. Perceived inadequate teacher subject knowledge may be a significant factor behind high teacher MA [37]. Most primary and secondary school teachers are female [71] and their MA affects students' MA and math performance [88]. Confusion about varied teaching methods can also lead to MA [16]. Teachers' perceived job satisfaction significantly influences their behavior in the classroom [109,114]. In particular, job dissatisfaction is related with a negative development in student achievement. Teacher–student relations affect achievement [92] and student engagement [108]. Some Asian students are exposed to extremely high-stakes exams, competition, school and parental pressure, and high workload keeping their anxiety high even if they are very high performers according to international standards [70]. Students in such high-stakes environments may especially benefit from consistent emotional teacher support [106].

Most cultures have gender stereotypes suggesting that males excel more in mathematics than females and such stereotypes are shared by parents and teachers alike. Such stereotypes can significantly impact the performance and self-esteem of girls and women [93]. While recent data suggest that 15-year-old girls are now at about the same level as boys in their math achievement [71], girls' subjective math self-concept and self-efficacy perceptions likely still lag behind boys' [70]. The term 'gender-equality paradox' refers to the fact that gender discrepancy in STEM fields is larger in more than less gender-equal countries [95]. Mothers in more gender-equal countries also rate their sons' mathematical expertise higher than that of their daughters with the exception of Scandinavian countries [96]. An analysis of 13 million Italian children's data found higher male advantage in mathematics performance in richer and more gender-equal Northern Italian than in Southern Italian regions, with the performance gap increasing through school [42].

The gender-equality paradox may appear because it may be easier or more acceptable for girls to follow their 'intrinsic interests' in more advanced countries [96] and consider non-math-related career options: higher pay associated with STEM careers may be less relevant for girls in rich countries as living standards are already sufficiently high, or they may earn as well in some non-STEM fields than in STEM fields [96]. Such 'intrinsic interests' may of course depend on further factors [82], such as on stereotypes and cultural attitudes about gendered STEM and non-stem career choices [11]. Consequently, educational freedom of choice in richer and often more gender-equal countries may in fact amplify the gender gap in STEM career choices, driven by perceived appropriateness and aptitude of girls for STEM fields. In such environments, the earlier pupils can opt out from optional math education, the more chance for gendered career choices to distract them from STEM careers. A similar mechanism may affect disadvantaged students who may perceive learning math as a high-cost venture with uncertain payout [46]. Individual lifelong career choices are unlikely to be based only on perceived academic strengths and utility [33,95]. Rather, emotional and cultural factors about the 'appropriateness' of some career paths also strongly affect choices. In fact, self-confidence in STEM abilities may also drive gender differences in pay within STEM fields [94].

Conclusions

Clearly, a very large number of biological, societal (educational), and individual factors interact in math development. These domains cannot be understood in isolation and their components' identity and their relations likely change through developmental time: a very extensive, changing causal network underlies math development. Data interpretation requires caution: most variables of interest are likely to be at least mildly correlated. Hence, testing a few constructs with high statistical power likely results in detecting significant correlations [101,105]. However, weak correlations between constructs have close-to-zero predictive power. Therefore, weak fragmented findings should not be overinterpreted. Researchers of mathematical development should be aware of the complexity underlying math development. The challenge is to discover the main organizing principles behind many interconnected developmental factors.

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Declaration of Competing Interest

There is no conflict of interest.

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