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Social determinants of mathematics and science achievement in historical context

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This review shows how the Sputnik shock in the USA and the reunification in Germany initiated comparative studies that shed light on the role of the economic, cultural, political and social contexts of education. The results of waves of research on factors of effective mathematics teaching have shown that different socio-political circumstances create different contexts (e.g. the degree of ability stratification, parental attention and teachers' expectations) for students' development and that these conditions strongly influence their affective characteristics. A number of important affective variables were identified, including self-concept, self-esteem, interest, curiosity and attitudes. Research findings described the mediating and moderating mechanisms of affective variables, e.g. how ability grouping influences mathematics self-concept, then how it impacts motivation and finally how it determines mathematics achievement. The experience from early comparative work was utilised in designing more comprehensive large-scale international assessment programmes with the aim of supporting evidence-based education.

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Introduction

Success in learning mathematics and science has traditionally been considered as a question of cognitive processes. As these school subjects are requiring relatively little external knowledge from other subjects, and consistent, using precisely defined concepts and strict logical rules, it seemed that learning them could be understood on the basis of a few rules and simple models. Early theories of cognitive development relevant to learning mathematics, such as Piaget's theory (with a focus on mathematical structures and operations), seemed to confirm this view. Mathematics and science curricula have been designed to strictly follow the logic of each discipline, and this seemed to be sufficient to ensure high-quality education. This approach worked in practice as well, when a few 'talented' students taught within this paradigm achieved well in these two fields. Those who did not were believed to be 'untalented'.

This simplistic model was challenged from two perspectives. First, some unexpected outcomes of cross-cultural comparisons highlighted the impact of broader social context (including cultural, political and economic issues) on educational achievement. Second, mass education required teaching practices that make mathematics and science education successful for all students, while efforts aimed at improving the quality of learning have shown that a number of other personality traits have to be taken into account beyond narrowly interpreted cognitive ones.

This experience led to intense research from both directions, both to understand the general social determinants of successful mathematics and science learning and to describe the impact of affective variables. Mathematics is the most 'culture-free' school subject; its content, especially in the first school years, may be the most international (universal). Nevertheless, it is taught with varying degrees of efficacy, so it is an ideal domain to study the factors of successful education. Therefore, mathematics learning attracts the attention of researchers interested in a number of aspects that influence students' cognitive development.

Historical events have an impact on the development of science as experience and newly emerging needs in a society call for scientific solutions. From the second part of the 20th century, this has been the case in education as well: scientific research is more often used to understand and solve problems faced by society. In this review, I show how historical events have prompted research on mathematics education and then how the results are applied to improve achievement. First, I illustrate this process through the example of two developed countries, the USA and Germany. Then I demonstrate (1) how research prompted by historical events has helped us to understand both the mechanisms of the impact of socio-political context and the mediating role of affective variables and (2) how an increased awareness of the complexity of education has contributed to the extension of international assessment programmes.

From the Sputnik shock to the first international assessments: the American experience

The first major cross-cultural comparison of the effectiveness of mathematics and science education was initiated by a historical event which was then followed by several other similar experiences that unexpectedly called the quality of education into question in certain developed countries. The first event, the Sputnik shock, occurred during the Cold War. The successful launch of the world's first satellite from the Soviet Union in 1957 prompted a series of comparative studies in the USA to reveal the reasons for this advanced technical capability, and the explanation was found in better mathematics and science education in the Soviet Union [33,72,89].

The first and second international mathematics and science studies provided more systematic confirmation of the poor achievement in the USA. For example, science achievement among 14-year-old American students dropped from 538 points (1970–71) to 491 points (1983–84) within a decade, ending in last place in the international rankings. During the same period, Japanese students improved from 578 to 592 points, and Hungarian students' scores rose from 584 to 626 ([37], p. 15). The decline between the former pairs of results directed the attention of the research community to Asian and Eastern European education. The drop-in mathematics was not so dramatic between the first (1964) and the second (1981–82) survey, but still alarming enough for the eighth-grade population, especially as the decrease was larger in the more demanding comprehension and application items. The average for the US students was around or below the international average for the eighth-grade sample and was very low (in the lowest quarter among participating countries) for the twelfth-grade sample, while the Japanese and Hong Kong students were the best achievers [52].

This experience made the improvement of education part of the political agenda in the USA, prompted immediate legislation and reforms [84], and inspired research programmes to uncover the reasons for the large differences in school achievement. As for Soviet education, the geopolitical conditions did not allow empirical research, so studies were limited to analyses and comparisons of curricula and teaching methods. Asian mathematics learning was an easier topic, as both Asian-American students, on the one hand, and Japanese and Taiwanese students, on the other, were assessable by means of tests and questionnaires.

A series of studies was conducted by Stevenson and his colleagues to explore what determines mathematics achievement by comparing American, Japanese and Taiwanese students, with participants from kindergarten to high school. An early study focused on a cognitive issue, comparing digit memory in Chinese and English. Chinese students achieved better. However, saying the digits that had been memorised out loud took approximately the same time in the two languages, and the results were considered as evidence for the temporally limited store [80]. The next phase of research examined social and affective issues. Significant differences were found in the three cultures in parental and family involvement of students' learning. Asian parents showed more interest in the academic achievement of their children, they had higher expectations, and they invested more effort into providing their children with a better learning environment. They evaluated their children more realistically, while American mothers overestimated their children's cognitive abilities and were more satisfied with their children's achievement. American mothers believed that innate ability plays a strong role in high achievement, while Chinese and Japanese mothers considered effort and diligence more important [19,22,74–76]. Chinese students spent more time attending school and afternoon classes [28], and large differences were found between American and Asian classroom structures and classroom management [81]. No differences were ascertained in the basic cognitive skills of American and Asian students, so the high mathematics achievement was attributed to differing school and home experience [79]. Valuing learning and knowledge, attitudes, beliefs and expectations were determined to be the most important variables to explain differences in mathematics achievement [78].

Comparing American and Asian students' learning to examine what determines mathematics achievement continued in the mid-1990s with the TIMSS (Third International Mathematics and Science Study) assessment and questionnaire data. This survey indicated the progress American education made as the late impact of efforts which followed a broader awareness of weak education: the USA was approximately in the middle of the international rankings [10,54]. Furthermore, two extensions of TIMSS focused on three countries: the USA, Japan and Germany. The TIMSS Videotape Study [36] used three cameras to video-record a student, the teacher and the whole class. Coding and careful analyses of the recordings revealed that there are large differences between the three cultures in the presentation of mathematical concepts, the role of teachers, the type of classroom discourse and students' work, among other areas. An ethnographic case study (interviews, conversations and observations) compared the daily lives of students, parents, teachers, administrators and policymakers in these three countries [11,73]. It was found that the more inspiring environment made Japanese students better problem-solvers, and, although they believed mathematics was more difficult to learn, they were more confident than their American counterparts.

From the post-reunification comparative studies to the Programme for International Student Assessment shock: the German experience

In Germany, two historical events initiated several waves of research which involved an exploration of factors that support learning mathematics. After the reunification of the former East and West Germany, the impact of culture and the different education systems on students' development became easy to compare. Since the geographical location, language and previous history were identical but socio-political and educational conditions were different, it was interesting to study how living in different cultures for several decades influenced students' personal characteristics, which then determined educational achievement. From an educational point of view, one of the most relevant differences was that the West German school system was highly selective, directing students to different tracks at an early stage of schooling, while educational policy in East Germany eschewed ability grouping and tracking [14].

A number of research projects took advantage of this unique opportunity in the 1990s, and the first studies explored the differences in school achievement and in personal characteristics among students raised and educated in the two cultures. Unexpectedly, students from the former East Germany (the Eastern states or *Neue Länder*) outperformed their western counterparts (in the Western states or *Alte Länder*). For example, in the first survey administered in the 1991–92 school year, students from the Eastern states achieved slightly better in mathematics and much better in physics and biology, with the difference in biology being nearly equal to almost a year of development [6].

As previous research had indicated that ability grouping has a powerful impact on students' self-concept (beliefs about oneself, see [69]) and that the relationship between self-concept and achievement is rather complex, understanding the phenomena required sophisticated theoretical models and research design to validate them. The situation after reunification offered an excellent context to test such models. First of all, a reciprocal effect may be postulated between academic self-concept and learning success, as high achievement improves self-concept and then positive self-concept increases the motivation to learn ([48]; see also [90]). Second, academic self-concept is subject-specific, so mathematical and verbal self-concept may be different; in addition, as many studies found little or zero correlation between them, they are actually different [93]. Furthermore, subject-related self-concept (beliefs about one's ability in a specific domain) requires reference points, and, in the case of self-concept, two frames of reference were identified, internally, comparing one's abilities at different domains (as mathematical and verbal), and externally, comparing one's capacities to others' (I/E reference model). Exploring the complex relationship between these variables leads to the discovery of the 'Big-Fish-Little-Pond Effect' (see [50,51,63]). This is a negative effect, which emerges when students are enroled in a class where class-average mathematics achievement is high, and this external reference lowers their mathematics self-concept. In other words, students with high mathematics ability feel less able (decreasing self-concept) when they are attending a class of students with high ability (external frame of reference).

Data collection covering the *Alte* and *Neue Länder*, including longitudinal surveys, allowed the unification of previous theoretical models. The results confirmed assumptions on the reciprocal effects of academic self-concept and achievement as well as the I/E reference model [49,83]. Other studies on non-cognitive characteristics bore similar results. For example, Hannover [31] found that East German students made more accurate self-related judgements and were less satisfied with themselves than their West German peers. These findings also confirmed the role of affective variables and contributed to an explanation for the higher achievement among the East German students.

The first wave of comparative studies was followed by TIMSS in 1995, which produced more comprehensive data sets and included an analysis of curricula and textbooks in the participating countries, as well as video recordings and ethnographic case studies in the USA, Japan and Germany. In Germany, the project was further extended with longitudinal data collection among the 7th- and 8th-grade students [7]. The main results of TIMSS indicated that the achievement of the 7th–8th-grade German students was about in the middle of the international scale. However, they reached the same level 6–12 months later than students in other countries, with the results being somewhat worse in mathematics than in science. The German TIMSS data allowed a more precise study of the east-west differences, and the findings were in line with previous ones. The common conclusions of the early comparative studies and TIMSS were that East German students performed consistently better than West German students [8,9].

TIMSS (1995) was repeated in 1999, under the name 'TIMSS-Repeat', and then it became a regular assessment programme with 4-year cycles. (The TIMSS acronym was kept with a new meaning: Trends in Mathematics and Science Studies.) TIMSS 1999 was also complemented with a video study with seven participating countries. These observations explored a number of features of mathematics classroom teaching, described the differences, and concluded that several methods may lead to high achievement, that there are no best methods, and that successful models thus cannot be exported from one country to another [82]. One of the main messages of these studies was that teaching methods alone do not determine mathematics achievement.

When the results of the first PISA (Programme for International Student Assessment, an OECD programme starting in 2000 and assessing students every three years) were published [4,57]. It attracted much broader public attention than previous reports. Although the results were not so terribly poor (490 points in mathematics, just one-tenth of a standard deviation below the 500 OECD mean), the unfavourable international rankings challenged what Germans believed about the quality of their education. Major German newspapers and television channels reported and discussed the results in special issues and on programmes for a number of months [30]. This intensive public debate had a long-lasting impact on education policy and school reforms in Germany ([24,29,39,55,68,85][94].

Research on education was already strong before the effect of PISA, which was marked by an important German extension of the first PISA survey, the assessment of dynamic problem-solving [88]. Its success later influenced the choice of the innovative domain in PISA 2012. Nevertheless, the PISA shock aided the further development of educational research and development. The large-scale German DFG Priority Programme "Competence Models for Assessing Individual Learning Outcomes and Evaluating Educational Processes" started in 2007 [46], and the Institute for Educational Quality Improvement was established in 2004 to run a national educational assessment system [40].

One of the main aims of educational research that followed the first PISA survey was to uncover the mechanisms that strengthen the relationship between students' social background and educational success. Recent studies [15,44] indicate that east-west differences last longer than expected; the impacts of the period of separated social development on education can be observed decades after reunification.

The main conclusions of research on the role of self-concept for German education policy were early treatment of the impact of social inequalities through day care [27] and reducing the selectiveness of the German school system by delaying the time when students are directed into different tracks [26], de-tracking (eliminating the non-academic track) and desegregation [44].

From Third International Mathematics and Science Study to the latest Programme for International Student Assessment surveys: the evolution of large-scale international assessments

Identifying the characteristics and factors that strengthen Asian mathematics education has remained a popular research topic until fairly recently, covering every detail of teaching and learning mathematics [42,45], for example, using modern technology for classroom observations, the values determining teachers' behaviour [70] and teacher education [41,87]. The Sputnik shock also remained a metaphor for a sudden realisation of poor educational achievement, especially as societies reacted similarly in such situations [32]. As the conclusion of a systematic review, Wang and Lin [86] confirmed the role of effort, students' self-concept and family expectations, in addition to the nature of the Chinese language as a possible explanatory factor. Dowker et al. [25] compared the mathematics knowledge of primary school English and Taiwanese children and found that Chinese students achieved much better. The negative effect of ability stratification mediated by the negative impact on self-concept has also been confirmed by current studies [63].

Recognising the importance of non-cognitive (social and affective) factors goes back for decades, and newer research directions carry on this tradition. Alken [1,2] pointed out the importance of a positive attitude (see also [38]), as well as enjoying and valuing mathematics. Reyes [67] highlighted the role of confidence in learning mathematics, attribution, learned helplessness and perceived usefulness of mathematics. Stevenson and Newman [77] showed the long-term predictive value of self-concept, expectancy for success, value of success and perception of task difficulty (see also [62,92]). Wong [91] identified attitudes towards mathematics, self- and parental expectations and academic self-concept as the strongest determinants of mathematics achievement, while other studies [3,16,34,43] confirmed that ability grouping has a strong impact on self-concept. Recent analyses showed that the differences in self-concept may explain boy-girl differences in mathematics achievement [53].

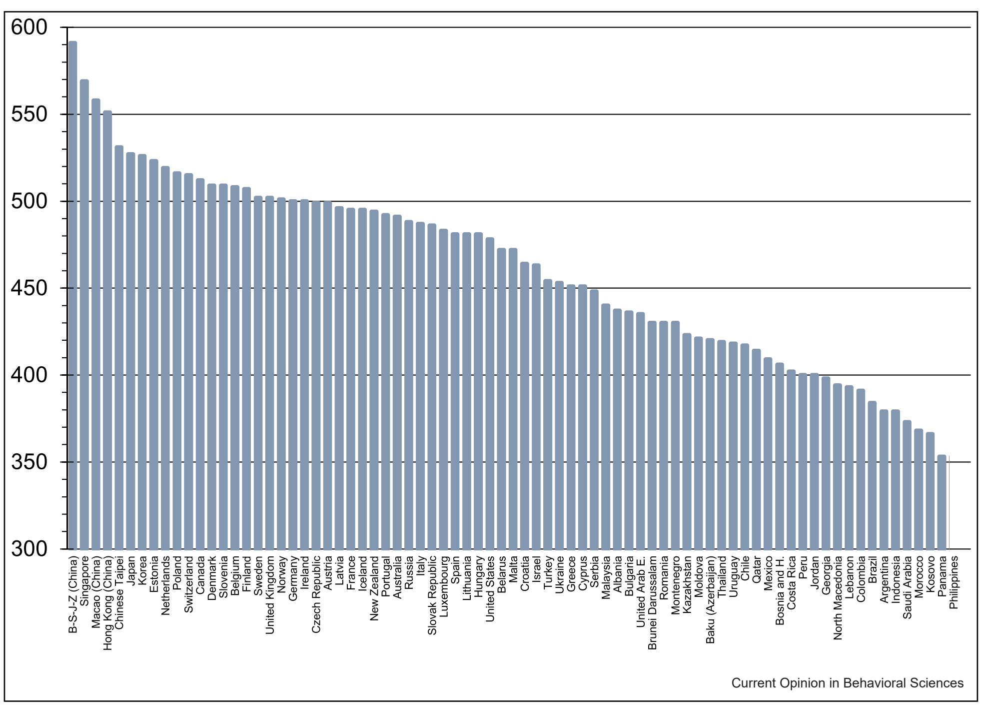
Nevertheless, further research on the factors that influence students' achievement demonstrated that personality traits or non-cognitive variables may play a more significant role than the cognitive ones [5,56], and the relationships may differ by gender [23,51]. Some research has explored the impact of socio-economic status and the mechanisms through which it influences mathematics achievement. In their review, Bradley and Corwyn [12] identified the mediating and moderating variables which link SES and children's development and others, and found belief in personal control, dispositional optimism, social support, self-esteem and coping strategies significant.

Neuroscience researchers also turned to the non-cognitive domain, arguing for the need for more complex models of learning [21]. Chen et al. [20] and Cargnelutti et al. [18] confirmed the role of affective factors from this perspective as well, from where mathematics anxiety seems a strong negative factor. As regards mathematics, anxiety was identified as one of the most relevant affective constructs to explain poor mathematics achievement [17,47,64,65].

When PISA was conceived in the late 1990s, it was devised to overcome the shortcomings of TIMSS (e.g. the grade-based sampling was replaced with age-based sampling). It led to new assessment frameworks so that achievement data could be interpreted in broader contexts, thus aiding policy more effectively. Preparation of questionnaires for students, parents, teachers and school principals utilised the rich results of previous research on social and affective factors. Data collected with these instruments has also made it possible to separate the effects attributed to schools (e.g. the positive school climate), the general impact of parents' SES and their personal involvement in their children's learning. Parents' emotional support was especially strong among resilient students [60].

Figure 1 displays the mathematics results from the most recent PISA assessment. East Asian countries dominate: China, Singapore, Japan and Korea. In Germany, the reforms, which included the development of new standards that place a greater emphasis on the type of competences assessed by PISA in mathematics (see e.g. [39]), led to visible but still slow improvement (10 points in PISA mathematics results over a decade); with its 500 points, Germany is at the level of the OECD mean. One of the reasons of the slow development is that the early tracking between schools still exist. The drop of the mathematics achievements in Hungary may also be attributed to growing selectivity of school system. Similarly, achievement of American students is below average (478 points), with a current level lower than in 2000 (493 points). During the same period, two Eastern European countries achieved remarkable development. Estonia (523 points) immediately follows the Asian countries, and Poland (516 points) is also close behind

Fig. 1



Mathematics results of the 2018 PISA assessment.
source: OECD, [58].

[35,58]. There is no tracking between schools in these two countries.

As PISA aims to provide data to compare school systems, its experts have devised a number of system-level indicators which can be used to explain the efficacy of education. Data show that although there is a positive relationship between spending per student and mathematics achievement, the available financial resources (e.g. spending per student) do not really matter a great deal in developed countries. Education systems where there is no tracking (the between-school differences are low) usually achieve better. Achievement is also better in countries where there is no strong link between SES and achievement and where the proportion of resilient students is high. Low SES students are usually less ambitious and less motivated to learn. High achievement is associated with more cooperation and less competition in schools. Achievement positively correlates with self-efficacy, clear learning goals, valuing learning, perceived competence and self-concept [58–61]. A number of studies have also explored the impact of PISA itself both from an international perspective (e.g. [13,71]) and at the country level as well (e.g. [66]). In general, countries that have already adopted the principles of evidence-based education policy and where there have been experts to transfer the results into local action have benefitted more from the rich PISA recommendations; furthermore, in some areas the changes have been easier (e.g. modifying the curricula and teaching methods, for example, in Germany, see [39]), while progress has been slower in domains that are socially more strongly determined (e.g. tracking practices).

Conclusions and further prospects for studying the social determinants of learning

In this review, I have analysed how historical events in two developed countries have directed attention to the poor achievement of the education system. In the USA, first the attention of the general public was caught by the launch of Sputnik in the Soviet Union, and then researchers explored the social and educational mechanisms of poor and high achievement. In Germany, in contrast, studies comparing the achievement of students socialised in East and West Germany were followed by the shocking experience of the early results of the first PISA survey (which were not so bad but below expectations).

These deficiencies became the most apparent through comparisons, most obviously in mathematics. Mathematics is a subject taught during the entire span of public education in almost every country; its curricula and content are the most universal and its mechanisms of learning the most intensively researched (from developmental through cognitive psychological to neuroscientific aspects). These features have thus made it an ideal domain for comparative studies. Exploring the factors that influence mathematics achievement led to discovering the decisive role of non-cognitive variables, social conditions, and the mediating and moderating roles of affective issues.

As accumulated results of related studies led to a better understanding of the importance of culture and sociopolitical context, a possible role of research in improving educational achievement also became apparent. It seemed possible that certain conditions which were created in spontaneous historical developments in some eastern countries (e.g. parental attention, teachers' expectations, belief in hard work, self-esteem and positive self-concept) could be created through scientifically established interventions. Recognising the value of scientific knowledge prompted the launch of national educational research programmes, as well as broadened the scope and strengthened the role of large-scale international assessments.

The spirit of evidence-based educational policy and data-based decision-making, including the most recent trends in exploiting the benefits of "big data", has become the norm in a number of developed countries. Of course, despite these intentions, the use of scientific knowledge is also changing from country to country and is affected by local culture, historical experience and political conditions.

Medicine and medical practice are often offered as a model for developing educational research and implementing evidence-based educational practice. The recent Covid-19 pandemic has shown the general public how scientific research works, what its power is and where its limits are. We have also come to see how the efficacy of the implementation of recommendations based on medical data is moderated by local culture and political conditions. Being one of the social sectors most significantly affected by the pandemic, education has provided a new impetus for educational research to deal with its social, economic and political embeddedness. Studying the historical context, as outlined in this review, may again be relevant in this context.

Conflict of interest statement

None.

Data availability

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