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ABSTRACT

Do Teachers' College Majors Affect Students' Academic Achievement in the Sciences? A Cross-Subfields Analysis with Student-Teacher Fixed Effects*

We examine whether and how teachers' major fields of study affect students' achievement, exploiting within-student variation across subfields in natural science (i.e., physics, chemistry, biology, and Earth science). Using middle-school students' data from the Trends in International Mathematics and Science Study and controlling student-teacher fixed effects, we find that teachers with college majors in natural sciences improve students' achievement of subfields in natural sciences corresponding to their subfields of college majors. Teaching practices explain about half of the effect of teachers' major fields. Most of the effects of teaching practices are accounted for by teachers' preparation for teaching science topics. The results are robust to potential endogenous matching between students and teachers.

JEL Classification: H75, I21, J24

Keywords: education, teacher, natural science, college major, middle school, TIMSS

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1. Introduction

Science literacy is one of the most critical determinants of success in the labor market. Altonji et al. (2012) and Kirkebøen et al. (2016) showed that science, technology, engineering, and math (STEM) majors are positively associated with earnings later in life. Card and Payne (2021) showed that most of the gender gap in STEM entry is due to differences in the share of college entrants who are STEM-ready. They also found that the gender gap in the likelihood of graduating with a STEM-related degree explains up to a fifth of the wage gap between young college-educated men and women in the United States and Canada. These findings indicate that promoting STEM education can be a policy measure to improve labor productivity and reduce the gender gap in wages.

Improving science teachers' quality is one of the key measures for enhancing students' science literacy. Researchers argue that teacher quality significantly impacts student learning outcomes (Hanushek and Rivkin, 2010). However, the predictive power of "observable" characteristics of teachers, such as gender and teaching experience, is generally limited (Hanushek and Rivkin, 2006). Measurement of teacher quality is not straightforward; hence, researchers and education administrators need to find observable characteristics of teachers associated with teacher quality to achieve optimal recruitment and assignment of highly qualified teachers.

Many researchers have studied the relationship between teachers' subject-related degrees, knowledge, and students' achievement as another observable predictor of teacher quality. To examine this relationship, they used various information, such as major fields (Chingos and Peterson, 2011; Croninger et al., 2007; Goldhaber and Brewer, 1997; 2000), subject-specific certification (e.g., Clotfelter et al., 2010; Dee and Cohodes, 2008; Goldhaber and Brewer, 2000; 2001; Sharkey and Goldhaber, 2008), teacher training (Backes et al., 2018; Harris and Sass, 2011), and more direct measures of a teacher's knowledge level, including teachers' test scores and grade point average (Bietenbeck et al., 2018; Boyd et al., 2009; Goldhaber et al., 2017; Hill, Rowan, and Ball, 2005; Kukla-

Acevedo, 2009; Metzler and Woessmann, 2012; Monk, 1994; Rockoff et al., 2011). A review by Coenen et al. (2018) argued that teachers' subject-related degrees and knowledge, particularly for mathematics and science, are positively associated with students' academic performance.[2] The mechanism of teachers' subject-related degrees and knowledge on students' academic performance are not very well understood, despite some studies finding a positive association between them.

This study examines whether and how teachers' majors affect students' achievement. In contrast to previous studies focusing on the relationship between teachers' majors and students' academic achievement at the subject level, such as language, mathematics, and science (Coenen et al., 2018; Wayne and Youngs, 2003), we study the relationship between science teachers' "subfields" in the natural sciences of college majors and students' performance in the corresponding subfields. Science taught in middle schools is generally divided into four subfields: physics, chemistry, biology, and Earth science. We exploit within-student variation across subfields in science to identify the effects of teachers' majors in natural science. Within-student variation across subfields enables us to estimate the effects of a teacher's college major, controlling student fixed effects "specific to natural science." Furthermore, we examine the primary determinants of these effects. This examination of the mechanism behind the effect of teachers' majors in natural science is one of our contributions.

In estimating the causal effects of teachers' major fields, it is necessary to consider potential biases due to endogenous matching between teachers and students. Ideal to estimate causal effects would be random student-teacher assignment within and across schools. However, assignment is rarely random because of school choice and optimal classroom formation (Clotfelter et al., 2006; Bonesrønning et al., 2005). For our research question, if unobserved characteristics are associated with both teachers' majors and students' science test scores, the estimates of the effect of teachers' majors will be biased. A typical strategy is to control students' fixed effects by taking within-student cross-

[2] Several studies reported that the effect of subject-related knowledge or degrees is greater in STEM subjects than in non-STEM subjects (e.g., Clotfelter et al, 2010; Goldhaber and Brewer, 1996; Metzler and Woessmann, 2012).

subject differences (Bietenbeck et al., 2018; Clotfelter et al., 2010; Dee, 2007; Hanushek et al., 2019; Metzler and Woessmann, 2012). This cross-subject differencing works well to eliminate subject-invariant fixed effects for both students and teachers when the same teacher teaches students different subjects. However, this may not resolve the issue when other teachers teach each subject and when teacher assignments are based on students' unobserved characteristics. We address this issue by restricting our sample to students taught by a science teacher responsible for all four subfields in science and controlling student-teacher fixed effects by exploiting the variation within students across subfields in science. Provided that student-teacher fixed effects are invariant across subfields, cross-subfield differencing identifies the impact of teachers' major fields in natural science on students' academic achievements by eliminating student-teacher fixed effects.

By estimating a model with data of middle school students, taken from the Trends in International Mathematics and Science Study (TIMSS) for 2003, 2007, and 2011, we find that students taught by teachers majoring in natural science fields improve their academic achievement in the corresponding subfields in science by 0.04 standard deviation. In addition, to remove potential bias due to endogenous matching between students and teachers, we estimate the same model with a sample of students who attend a school that is assumed to have only one class in the grade and find that the results are robust.[3] Teachers who majored in a specific field of natural science would be more likely to improve students' achievement not only in the field but also in other fields of it. If these spillover effects exist, the estimates here are considered lower bounds because of the spillover effects of teachers' major fields.

[3] A recent working paper employed a similar identification strategy with the TIMSS data to account for student fixed effects by exploiting the variation within students across subfields in science (Sancassani, 2021). Since the focus of this paper is to examine the effect of teacher characteristics (including subfields in science) on students' science achievement, the sample was restricted to students from countries where the subfields in science are taught by "different" teachers. In contrast, the main focus of our paper is to identify the effects of subfields in natural science of teachers' major fields and its mechanism "controlling student-teacher fixed effects" by restricting our samples to students taught by "same" teachers. The first draft of our paper was written in November 2020 without any awareness about this previous paper, which, however, is complemented by our paper.

To understand the mechanisms behind the effect of teachers' major fields, we investigate the relationship between teachers' major fields and their teaching practices. We find that teachers who majored in a natural science field tend to prepare well to teach science topics, allocate more time, and teach a broader range of subfields corresponding to the major field. In addition, we conduct an analysis to examine the extent to which these teaching practices explain the effects of teachers' majors. We find that the degree of preparation to teach science topics explains about 22% of the effect of teachers' major fields, which is the largest ratio among other channels, such as time allocation and range of teaching topics. This result suggests that teachers' majors in natural science positively affect students' academic outcomes by improving the quality of their preparation for teaching. Furthermore, about 50% of the effect remains unexplainable, implying that the unobservable quality of teachers associated with their major fields plays a vital role in improving students' academic achievement. We also find heterogeneity in the effects of teachers' major fields: the positive effect is more substantial for students taught by teachers with a greater number of major fields, female students, and students with a high level of ability.

The remainder of this paper is organized as follows. Section 2 discusses the empirical strategy. Section 3 elucidates our data and reports summary statistics. Section 4 presents the main effects of teachers' subfield majors. Section 5 discusses the potential mechanisms behind these effects. Section 6 presents heterogeneous effects. Section 7 concludes.

2. Econometric Framework

To investigate the effect of teachers' majors in natural science on students' academic achievement, we estimate the following regression model:

$$Y_{ifj} = \beta Major_{fj} + \delta_f + \eta_{ij} + \varepsilon_{ifj} \qquad (1)$$

where Y_{ifj} is the science test score of student i in subfield f in class j. $Major_{fj}$ is an indicator that represents whether the teacher's major fields in natural science and the subfields of the student's test score match, and thus, β is the coefficient of our primary interest. δ_f is the subfield fixed effect. η_{ij} is the student-teacher fixed effects, controlling for any subfield-invariant determinants of science test scores attributable to the pair of student i and teacher j. ε_{ifj} is an error term. To show the importance of controlling student-teacher fixed effects, we present the ordinary least squares estimation results without student-teacher fixed effects too.

The identifying assumption of the model parameters is that the error term is orthogonal to teachers' major fields $Major_{fj}$ conditional on student-teacher fixed effects. A potential threat to identification is sorting students into teachers within a school based on students' subfield-specific unobservables. For example, if students are more capable of studying physics than other subfield subjects, and science teachers who majored in physics are systematically assigned to these students, the estimates are biased. To confirm the robustness of the results against potential endogenous matching between students and teachers based on students' subfield-specific unobservables, we restrict our sample to small schools with only one class in the grade, wherein multiple science teachers in the grade are unlikely. Standard errors were clustered at the class level, accounting for the correlation in outcomes among students in the same class.

3. Data

The data used in this study include information on middle school students taken from the TIMSS survey for 2003, 2007, and 2011.[4] TIMSS, an international survey conducted every four years, measures the mathematics and science achievement of fourth- and eighth-grade students and students',

[4] We excluded TIMSS 2015 and 2019 survey because the published dataset does not include enrollment information used for a robustness check in this paper.

homes', teachers', and schools' characteristics, as well as curricular backgrounds in participating countries and regions. For example, 608,641 students, 49,429 teachers, and 19,612 school principals from 63 countries participated in the fifth survey conducted in 2011.

Each student's test scores in each subfield of science (i.e., physics, chemistry, biology, and Earth science) have five plausible values (PVs) in the TIMSS dataset.[5] PVs were generated by exploiting the item response theory method based on the results of the tests and questionnaires. The mean of the national average scores is 500, and the standard deviation is 100 for all countries participating in TIMSS 1995.[6] In all estimations, we use "student senate weight" included in the dataset that rescaled the student sampling weight to give the same weight to each country because we use student samples from several countries.[7] In addition, we estimate the models using each of the five PVs separately and report the average of the five estimates.

This study excludes samples of students taught by more than one science teacher from the analysis because when multiple teachers teach science classes, sorting between students and teachers can occur across subfields, potentially causing bias in the estimation. We compile student data from the four subfields to estimate the student-teacher fixed effects model that compares within-student cross-subfields in science. The sample for the estimation consists of 219,220 middle school students and 10,927 science teachers from 10,907 science classes in 9,378 schools from 49 countries worldwide. The size of the pooled samples from the TIMSS of 2003, 2007, and 2011 is 513,295, excluding students who could not be linked to their science teachers and who had multiple science teachers. We exclude samples with missing values for any variable used in the estimation, as listed in Table 1.

5 Samples were extracted by employing the two-stage random sample design where schools are selected as a first stage and classes are selected as a second stage. TIMSS uses a matrix-sampling booklet design, in which each student is administered only a subset of the entire TIMSS item pools to cover a wide range of topics. Therefore, not all participating students took the same test.

6 PVs are multiple imputations of the unobservable latent achievement for each student (Wu, 2005). For more detailed information about the methods and procedures in TIMSS, see Martin and Mullis (2012).

7 For example, Woessmann (2011) and Hanushek et al. (2015) used international survey data such as PISA and PIAAC, and conducted weighted analyses with same weights for each country.

[Table 1]

Table 1 reports the descriptive statistics of the variables: students' academic achievement, teachers' majors, teaching practices, and demographics. As shown in Table 1, the fraction of teachers' major fields matching a subfield of science test scores (i.e., the mean of $Major_{fj}$) is 31.6 percent.[8] Since this fraction would be 25 percent if all teachers majored in only one of the four fields in natural science, and 50 percent if all of them majored in two of the four fields, the result of 31.7 percent implies that, on average, science teachers majored in more than one subfield but less than two subfields. In terms of each field, the proportion of teachers majoring in biology is relatively higher, whereas the proportion of those majoring in Earth science is much lower than the other two subfields.[9] Regarding the number of fields teachers majored in, the percentage of teachers who majored in only one field is the highest at 41%, whereas the percentage of teachers who majored in all four fields is the lowest at 6.7%.

Regarding student academic outcomes, the mean of the students' test scores is 471, and the standard deviation is 116, including all subfield test scores. There is almost no difference in score distribution across the subfields.[10]

TIMSS also contains information about teaching practices in each subfield, which we use to investigate the relationship between teachers' major fields and teaching practices. We construct an indicator of teachers' preparation to teach science topics in each subfield by using the following question for teachers: "How well-prepared do you feel you are to teach the following science topics?" This question has several items about science topics in each subfield, and teachers are asked to choose

[8] Details of science teachers' major fields are gathered in the questionnaire for teachers. Teachers are asked to choose "yes" or "no" for each major field, including physics, chemistry, biology, and Earth science.
[9] While the ratio of science teachers who majored in Earth science is small and may have unique characteristics that cannot be observed, robust results are obtained when Earth science is excluded from the data set. We can provide the results upon request.
[10] While the TIMSS 2007 and 2011 included test scores for the following four subfields in science: biology, physics, chemistry, and Earth science, the TIMSS 2003 include following five subfields test score: life science, physics, chemistry, Earth science, and environmental science. We regard the scores in life science in the TIMSS 2003 as the scores in biology. All results in this paper are robust when the samples of TIMSS 2003 are excluded.

from “Not applicable,” “Very well prepared,” “Somewhat prepared,” and “Not well prepared.” When a topic is not in the eighth-grade curriculum or teachers are not responsible for teaching the subjects, they are asked to choose “Not applicable.” We score 1, 2, and 3 when teachers chose “Not well prepared,” “Somewhat prepared,” and “Very well prepared,” respectively, and the average score for each subfield is used as an indicator of teachers’ preparation to teach science topics.[11] As shown in Table 1, the mean of the teachers’ preparation scale is 2.56 when all subfields are included. This means that the readiness of teachers to teach science topics, on average, is somewhere between “Very well prepared” and “Somewhat prepared.” Focusing on each subfield, while teachers are relatively well prepared in chemistry, they are not prepared in Earth science. Furthermore, Table A1 shows the correlation coefficients between teachers’ major fields and the preparation status for teaching science topics, indicating that teachers are better prepared for the subfields corresponding to their major fields than other subfields.

Next, we construct an indicator for teaching time allocation in each subfield using the following item: “By the end of this school year, approximately what percentage of teaching time will you have spent during this school year on each of the following science content areas for the students in this class?” Teachers are asked to respond to the percentage for each subfield, such that the total is 100 percent.[12] As shown in Table 1, the total average of the four subfields is approximately 92 percent, indicating that these four are the main areas taught by science teachers. Teachers spend less time on Earth science than others, focusing on each subfield.[13] Furthermore, Table A2 shows the correlation

[11] Regarding teachers’ preparation to teach science topics, when more than one-third of the question items in a subfield are missing or “Not applicable,” we put a missing value in the indicator of teachers’ preparation. The number of items in each subfield are as follows: in the order of the 2003, 2007, and 2011 TIMSS survey, 5, 7 and 7 in biology; 5, 5, and 4 in chemistry; 5, 6, and 5 in Physics; 3, 5, and 4 in Earth science.
[12] While the TIMSS 2007 and 2011 have five science subfields in this question: biology, physics, chemistry, Earth science, and others, the TIMSS 2003 has six: life science, physics, chemistry, Earth science, environmental science, and others. We regard the answer in the life science area in the TIMSS 2003 as the answer in the biology area.
[13] The minimum value of the variable “Time allocation” is 0 and the maximum value is 100, indicating that some of the teacher sample teach only one specific subfield in a year. In the robustness check section, we only present results of teachers who teach all subfields in science in a year and thus, show that our results are robust.

coefficients between teachers' major fields and teaching time allocation, indicating that a slightly more time is spent on the subfields corresponding to the teachers' major fields than on other subfields.

Finally, we evaluate the range of topics taught in each subfield using the following question: "Choose the response that best describes when the students in your class have been taught each topic."[14] This question has many items that describe the main topics addressed by the TIMSS Science Test. If a teacher chooses "Mostly taught before this year" or "Mostly taught this year," we assume that they had already taught the topic. As shown in Table 1, the mean percentage of the range of topics taught is 67.5 percent. Focusing on each subfield, the percentage of Earth science topics is 59.1 percent, lower than approximately 70 percent of the others. Furthermore, Table A3 shows the correlation coefficients between teachers' major fields and the range of topics taught, indicating minimal correlation between them. This result may be because the national and school curricula regulate the teaching content, and teachers do not have much discretion regarding what to teach.

TIMSS also contains rich information on students, family, teachers, and school characteristics, such as students' gender, parents' education, teachers' gender, years of teaching, class size, and enrollment in the grade. We use these pieces of information as covariates in the regression analysis, robustness check, and exploration of the heterogeneous effects of teachers' major fields.

4. Results

This section presents the results of regression analysis using Eq. (1). First, we explain the main results. Then, we discuss the robustness of our main findings.

[14] Teachers are asked to choose "Mostly taught before this year" if a topic was in the curriculum before the eighth grade. If a topic was partially taught in this year but not yet completed, they are asked to choose "Mostly taught this year." If a topic is not in the curriculum, they are asked to choose "Not yet taught or just introduced." When more than one-third of the question items in a subfield are missing, we put a missing value in the indicator. The number of the items in each subfield as follows: In the order of the 2003, 2007, and 2011 TIMSS survey, 12, 14 and 7 in biology; 8, 8, and 4 in chemistry; 10, 10, and 5 in Physics; 11, 14, and 4 in Earth science.

4.1. The effects of teachers' major fields on test scores

Table 2 shows the estimated coefficients of the dummy variable indicating the match between teachers' major subfields in science and students' test subjects. We report the results for four specifications in column order: (1) including year fixed effects, subfield fixed effects, and country fixed effects; (2) adding student and family controls: students' gender and parents' education; (3) adding teacher and school controls: teachers' gender, years of teaching (quadratic polynomial), class size (cubic polynomial), enrollment in the grade (cubic polynomial), and (4) controlling student-teacher fixed effects.

[Table 2]

The results show that the relationship between teachers' majors and students' achievement is positive and statistically significant (Column (1)). This positive relationship is stable after controlling for student and family characteristics (Column (2)) and teacher and school characteristics (Column (3)). The coefficient in Column (3), 5.0081, implies that the subfield score of students taught by teachers who majored in that subfield in college is higher by 0.05 standard deviation than those teachers without a college major in that subfield.

Column (4) presents the estimation results with student-teacher fixed effects. The teachers' majors' field dummy coefficient remains positive and statistically significant. The estimated coefficient, 4.6485, is slightly lower than the estimate in Column (3), suggesting that the estimates without controlling for student-teacher fixed effects may be biased upward because of a positive correlation between teachers' major fields and unobservable determinants of student achievement in subfields.

Although we obtained a positive and statistically significant effect of teachers' subfield majors, the estimated effects may be underestimated due to spillover effects from one subfield to the others. For example, a teacher who majored in physics may improve students' achievement in physics and the achievement of other subfields in science. If these spillover effects exist, our estimates can be considered to present a lower bound for the effects of teachers' major fields.

4.2. Robustness

The student-teacher fixed effects model identifies the effects of teachers' majors if the matching between teachers and students is orthogonal to the comparative advantage of students across subfields in natural science. The model with student-teacher fixed effects addresses the issue of endogenous matching between students and teachers based on "absolute ability," which is common to all subfields in natural science. However, one may be concerned that the estimate in Column (4) may be derived from the sorting of students into schools or teachers based on students' "subfield-specific" unobservables ("comparative ability"). For example, in cases where a student who is better at physics than other subfields selects a school with a high proportion of science teachers who majored in physics, or where a teacher who majored in physics is assigned to a class with students who are better at physics than the other subfields, the estimates are biased upward. We check whether these sorting mechanisms between and within schools may be a serious concern in the estimation of Column (4) in Table 2 by restricting the sample to those in small municipalities—where it is unlikely that there are schools that specialize in a particular subfield in science—and to those in schools with only one class and one science teacher in a grade where within-school matching between students and teachers based on comparative ability hardly occurs. Additionally, to eliminate schools or teachers that specialize in a particular subfield, we present results with the sample restricted to those who have teachers teaching all four subfields, spending an instructional time of at least 10% and 20%.[15]

First, to confirm whether there exist any between-school sorting effects, we restrict the sample to students living in small municipalities with a population of less than 15,000, wherein schools

[15] The robustness check here uses an approach similar to the one used by Bietenbeck et al. (2018).

specializing in a particular subfield in science are unlikely. The results in Column (1) of Table 3 show that the estimated effect is almost the same as in Column (4) of Table 2. This result suggests that the potential sorting of students into schools based on their comparative ability across subfields in natural science is not a serious concern in our sample.

Second, we restrict the sample to students in schools with only one class in the grade, where it seems unlikely that multiple science teachers teach one grade.[16] Column (2) of Table 3 reports the estimation results for restricted samples. The coefficient is 3.5778, slightly lower than the estimate in Column (4) of Table 2, suggesting a positive within-school correlation between teachers' major fields and unobservable student achievement determinants of subfield. However, the estimate in Column (2) of Table 3 remains statistically significant, suggesting that the reported positive effect of college majors in Column (4) of Table 2 is robust for the possible sorting of students to teachers within a school.

Third, to eliminate schools or teachers specializing in a particular subfield, we restrict the sample to those in which the teachers' instructional timeshare is at least 10% and 20% in each subfield. Columns (3) and (4) of Table 3 report that the coefficients are positive but smaller than the estimate in Column (4) of Table 2. There are at least two ways to interpret these results. First, we consider student sorting: A group of students who were originally good at specific subfields was assigned to a teacher who majored in the corresponding fields and had a large proportion of teaching hours in the subfields, causing an upward bias. The second interpretation considers the loss of the partial effect of teachers' major fields. Teachers who majored in an area in natural science tended to increase their instructional timeshare in the subfields corresponding to their major fields, resulting in relatively higher student performance in the other subfields. Although the results of columns (3) and (4) of Table

[16] While TIMSS does not include information about the number of classes in the grade, it obtains enrollment in the grade from school questionnaires and class size from teacher questionnaires. We, therefore, define the student sample who attend schools where the enrollment in the grade does not exceed the class size as students who attend schools with only one class in the grade.

3 could include either interpretation, the coefficients on major in fields taught remain positive and statistically significant, suggesting the robustness of our result in Column (4) of Table 2 to the potential sorting of students to schools and teachers. In the next section, we explore the possible mechanisms accounting for the positive effect of teachers' college majors.

5. Mechanism

Recent studies have shown that some teaching practices substantially impact educational outcomes (Schwerdt and Wuppermann, 2011; Van Klaveren, 2011; Bietenbeck, 2014; Lavy, 2016; Tanaka and Ishizaki, 2018; Motegi and Oikawa, 2019). It is possible that differences in teachers' majors may cause differences in their knowledge and teaching practices, affecting students' academic achievement. In this subsection, we analyze the relationship between science teachers' major areas and teaching practices to understand the positive effects of teachers majoring in natural science fields on students' academic achievement.

Understanding the mechanisms of the effects of teachers' majors is very helpful in policymaking and school administration too because it sheds light on practical and accessible ways to improve student outcomes. For example, if a teacher does not have majors in the subfields of science for which they are responsible, the principal would assign another teacher with science majors. In case where such a teacher arrangement is infeasible, the principal could provide teachers with training and other educational opportunities to encourage them to improve the quality of their teaching, especially in terms of preparation for teaching science topics.

To investigate the effect of teachers' majors on their teaching practices, we use three indicators of teaching practices in each subfield described in Section 3: (1) teachers' preparation to teach science topics, (2) teaching time allocation, and (3) the range of science topics being taught. We investigate whether teaching practices change depending on teachers' major fields by estimating the following regression model (2):

$$Teaching^{k}_{fj} = \alpha^{k} Major_{fj} + \delta_{f} + \eta_{ij} + \varepsilon_{ifj} \qquad (2)$$

where $Teaching^{k}_{fj}$ is the teaching practice k of teacher j in subfield f.

[Table 4]

Table 4 presents the estimates of the coefficients, α^{k}. These results show that teachers tend to prepare well for teaching and spend more time teaching a broader range of subfields that correspond to their major fields. Overall, there is a tendency for teachers to exert greater effort into subfields that correspond to their major fields.

To understand the extent to which each channel of teaching practices explains the effect of the teachers' major fields, we conduct a mediation analysis, following Heckman et al. (2013). Specifically, we include the variables of teaching practices in Eq. (1) and consider the following model (3).

$$Y_{ifj} = \zeta Major_{fj} + \sum_{k} \theta^{k}\, Teaching^{k}_{fj} + \delta_{f} + \eta_{ij} + \varepsilon_{ifj}. \qquad (3)$$

Coefficient ζ represents the effect of teachers' major fields, which is not explained by the observed change in teaching practices. As a result, the ratio of the effect of teachers' major fields explained by the combined differences in the observed change in teaching practices is given by $1 - \zeta / \beta$. The ratio of the effect of the teachers' major fields attributable to the kth teaching practice can then be calculated by $\theta^{k}\alpha^{k} / \beta$.

[Table 5]

Table 5 presents the estimation results for Eq. (3), suggesting that these three teaching practices are positively related to students' academic achievement (Columns (2) to (5) in Table 5). The coefficient of majors in fields being taught in Column (5) is 2.3526, smaller than that in Column (1). This result suggests that the positive effect of teachers' majors can be interpreted through the mechanisms of the three teaching practices. Still, most of the positive effect remains unexplained by observable teaching practices.

Figure 1 plots the estimated results of decomposing the effects of teachers' major fields on student achievement into these three teaching practices and unexplained factors. We find that half of the positive effect of teachers' college major can be accounted for through the difference of teaching practices: 21%, 16%, and 12% of the overall effectiveness of teachers' major fields is through the mechanisms of preparation, time allocation, and instructional coverage, respectively. Even after considering teaching practice, half of the positive effect of teachers' college major remains unexplained.[17] These results are broadly consistent with the findings in the literature wherein a large part of teacher effects is unobservable.

6. Heterogeneous effects

The estimate of Eq. (1) captures the average effects of teachers' major fields in natural science on students' academic achievement in the corresponding subfields. Still, the effects may differ across students' and teachers' characteristics, such as teachers' qualifications and experiences, and students' gender and ability. We estimate Eq. (1) with interaction terms between teachers' major fields being taught and factors that may cause heterogeneity in effects.

[Table 6]

First, to explore whether the deeper expertise of teachers in major fields increases the positive effect, we add the interaction term between "Major in fields taught" and the possession of a master's degree or higher. The estimated coefficient reported in Column (1) of Table 6 indicates that the effect

[17] When we restrict the sample to students who are in schools with only one class in the grade, we find that 39% is through the mechanisms that cannot be explained. The ratio is smaller than that in Fig.1, which is the result when we do not consider the within-school sorting of students based on students' subfields specific unobservables. This suggests that part of the 50%, that is, the mechanism through unexplained factors in Fig.1, may include the influence of student sorting within schools.

of teachers' majors is smaller for those with a master's degree. Still, the difference is not statistically significant, implying that to improve student science achievement, science teachers need to have a degree in the subfields that are acquired at the bachelor's level but not to the depth of it at the master's level.

To explore whether having a more comprehensive range of major fields increases the effect, we add the interaction term between "Major in fields taught" and the number of teachers' major areas. Column (2) of Table 6 shows that, compared to teachers with only one major field in natural sciences, teachers with two and three major fields in natural sciences have larger positive effects on student achievements by 0.016 and 0.045 standard deviations, respectively. The results suggest that science teachers with broader major areas improve student achievement.[18]

Furthermore, to explore whether teaching experience complements teachers' lack of expertise, we add the interaction term between "Major in fields taught" and years of teaching experience. Column (3) of Table 6 reports the estimate of the effect of teachers' majors. The effect seems smaller for those with longer teaching experience, but the difference is not statistically significant.[19] This result implies that the lack of a major field in natural science is not supplemented by accumulating teaching experience.

[Table 7]

Next, we examine whether the effect of teachers' major fields differs depending on the student characteristics of gender and ability by adding the interaction terms. Using math test scores as a proxy measure of student ability, we divided students into upper, middle, and lower groups. The results show

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[18] Teachers who have broader major fields may indicate greater competence. In fact, the average number of major fields in the natural sciences for teachers who hold a master's degree or higher is 1.39, which is higher than the average of 1.24 for teachers who do not. The result is still robust when we estimate the model with the interaction term of "Major in fields taught" and the possession of a master's degree or higher added to Table 6, Column 2. Therefore, it is plausible to interpret the results in Table 6, Column 2 as indicating that the effects of major fields vary based on differences in the breadth of teacher expertise, rather than differences in teacher ability.

[19] Instead of the variable of years of teaching, we also add the interaction terms with dummy variables for years of teaching, but no statistically significant results are obtained.

that the effect of teachers' majors is larger for female students (Column (4)) and students with a higher ability (Column (5)). These results are consistent with previous studies (Metzler and Woessmann, 2012; Sancassani, 2021).[20] Teachers' majors likely differ depending on the students' ability because the students who are more capable are taught more specialized content and can understand it.

Finally, we examine whether the effect of teachers' major fields differs among science subfields. We add the interaction term between "Major in fields taught" and each subfield dummy variable. The results reported in Column (6) of Table 7 suggest that the effect of teachers' majors varies by subfield. In descending order of the degree of the effect of teachers' major fields, chemistry is the largest, followed by physics, biology, and Earth science. While the effect of teachers' majors in chemistry improves student achievement by 0.07 standard deviations, the effect of teachers' majors in Earth science is positive but statistically insignificant.

7. Conclusion

This study examined the effect of teachers' majors on the science test scores of middle-school students using student-teacher matched data from the TIMSS for middle school students across the world. Information specific to science subfields enabled us to exploit variation across subfields within students and thus estimate causal relationships between teachers' major fields and student achievement.

We found that eighth-grade students taught by teachers with majors in the natural science field improved their achievement in science subfields by 0.05 standard deviations corresponding to teachers' major fields, compared to those taught by teachers without it. Exploring the potential mechanisms through which teachers' majors play a role reveals that teachers improve their preparation for teaching, increase their time allocation for teaching, and expand the range of teaching topics in the subfields

[20] On the heterogeneity in students' gender, Sancassani (2021) found that while teacher expertise has a positive effect on female students' test scores, it is positive, but not statistically significant, on male students' test scores. On the heterogeneity in students' abilities, Metzler and Woessmann (2012) found that teachers' rich subject knowledge influences the academic performance of high-achieving students. Sancassani (2021) found that teachers with expertise have positive and significant effects only on students with high socioeconomic status.

corresponding to their major fields. These mechanisms of teaching practices explain roughly half of the effects of teachers' majors. In particular, improving the quality of their preparation for teaching explained approximately 21 percent of the effects. Observable teaching practices cannot explain roughly 50 percent of the mechanisms of the effect of teachers' major fields, which may suggest that the unobservable quality of teachers associated with their major fields plays a vital role in improving the academic achievement of students.

Our findings make several contributions to the literature and have policy implications. First, whereas most of the literature focuses on the effects of teachers' subject-specific knowledge on students' academic performance in subjects such as mathematics and science, our study provides evidence on the impact on students' performance in each subfield of science using a cross-subfield analysis with student-teacher fixed effects. Second, we provide evidence of the mechanism that drives the effects of teachers' major fields, namely teaching practices. Third, we provide evidence of the heterogeneity in the effects of teachers' majors in natural science across the characteristics of teachers and schools. These findings shed light on educational policies designed to improve students' outcomes in science. For example, our results suggest that assigning science teachers to teach subfields that correspond to their major fields is beneficial. One way to compensate for teachers without majors in natural science fields could be to provide them with training opportunities to acquire expertise and pedagogy in natural science and apply it to their teaching practices, which may achieve outcomes similar to those of having natural science majors.

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Table 1. Summary statistics

	Mean	S.D.	Min.	Max.
Outcome variables:				
Test score	471	116	5	912
Test score in Physics	469	117	5	882
Test score in Chemistry	468	116	5	912
Test score in Biology	473	115	5	879
Test score in Earth Science	472	117	5	880
Independent variables:				
Teacher				
Major in fields taught	0.317	0.465	0	1
Major in Physics	0.300	0.458	0	1
Major in Chemistry	0.385	0.487	0	1
Major in Biology	0.426	0.495	0	1
Major in Earth Science	0.154	0.361	0	1
Number of major fields in natural science	1.266	1.166	0	4
one	0.409	0.492	0	1
two	0.144	0.351	0	1
three	0.101	0.301	0	1
four	0.067	0.250	0	1
Preparation	2.56	0.50	1	3
Preparation in Physics	2.55	0.49	1	3
Preparation in Chemistry	2.64	0.48	1	3
Preparation in Biology	2.59	0.47	1	3
Preparation in Earth Science	2.46	0.55	1	3
Time allocation	0.230	0.138	0	1
Time allocation in Physics	0.257	0.121	0	1
Time allocation in Chemistry	0.232	0.117	0	1
Time allocation in Biology	0.272	0.150	0	1
Time allocation in Earth Science	0.159	0.133	0	1
Range of topics taught	0.675	0.291	0	1
Range of topics taught in Physics	0.696	0.261	0	1
Range of topics taught in Chemistry	0.722	0.285	0	1
Range of topics taught in Biology	0.689	0.261	0	1
Range of topics taught in Earth Science	0.591	0.333	0	1
Female teacher	0.524	0.499	0	1
Teaching experience	12.6	9.3	0	50
Graduate degree	0.176	0.381	0	1
Class size	32.0	9.8	1	116
School				
Grade 8 Enrollment	180.9	162.5	1	1661
Student and Family				
Girl	0.506	0.50	0	1
Parents' education (college degree or higher)	0.283	0.45	0	1
Year				
2011	0.256	0.44	0	1
2007	0.412	0.49	0	1
2003	0.332	0.47	0	1

Note: Number of observations is 876,880.

Table 2. The effects of teachers' major fields on academic achievement

	Physics + Chemistry + Biology + Earth Science			
	OLS			FE
	(1)	(2)	(3)	(4)
Major in fields taught	5.2161***	4.8776***	5.0354***	4.6485***
	(0.8497)	(0.8047)	(0.7953)	(0.3259)
Student and family controls	No	Yes	Yes	abs.
Teacher and school controls	No	No	Yes	abs.
Observations	876,880	876,880	876,880	876,880
R-squared	0.369	0.393	0.398	0.920

Notes: Students and family controls include gender, parents' education. Teacher and school controls include gender, experience (quadratic polynomial), and whether they have a graduate degree, class size (cubic polynomial) and enrollment in the grade (cubic polynomial). All regressions include year fixed effects, subfields fixed effects, and country fixed effects, and give same weight to each country. Standard errors are clustered at class level and reported in parentheses. * p < 0.10; ** p < 0.05; *** p < 0.01.

Table 3. Robustness check

	Rural area (15,000 people or fewer in the area)	One class in the grade	Teachers' instructional time share is at least 10% in each subfield	Teachers' instructional time share is at least 20% in each subfield
	(1)	(2)	(3)	(4)
Major in fields taught	4.9623***	3.5778***	3.5135***	2.6817***
	(0.6732)	(1.2473)	(0.3957)	(0.6484)
Observations	261,220	99,732	598,828	232,712
R-squared	0.914	0.907	0.920	0.925

Notes: The table shows fixed effects regressions of student scores on teachers' major fields being taught with restricted sample shown in each column. All regressions include subfield fixed effects, and give same weight to each country. Standard errors are clustered at class level and reported in parentheses. * p < 0.10; ** p < 0.05; *** p < 0.01.

Table 4. Mechanism: Teaching practices

	Preparation	Time allocation	Range of topics taught
	(1)	(2)	(3)
Major in fields taught	0.3515***	0.0672***	0.0378***
	(0.0074)	(0.0033)	(0.0043)
Observations	876,880	876,880	876,880
R-squared	0.646	0.166	0.547

Notes: The table shows fixed effects regressions of teaching pratices on teachers' major fields being taught. All regressions include student-teacher fixed effects and subfield fixed effects, and give same weight to each country. Standard errors are clustered at class level and reported in parentheses. * p < 0.10; ** p < 0.05; *** p < 0.01.

Table 5. Mediation Analysis

	Physics + Chemistry + Biology + Earth Science				
	(1)	(2)	(3)	(4)	(5)
Major in fields taught	4.6485***	2.5321***	3.4147***	3.9831***	2.3526***
	(0.3259)	(0.3555)	(0.3248)	(0.3173)	(0.3437)
Preparation		6.0217***			2.8347***
		(0.4048)			(0.4108)
Time allocation			18.3498***		10.9235***
			(0.9864)		(0.9849)
Range of topics taught				17.6111***	14.9581***
				(0.6561)	(0.7023)
Observations	876,880	876,880	876,880	876,880	876,880
R-squared	0.920	0.920	0.920	0.921	0.921

Notes: The table shows fixed effects regressions of student scores on teachers' major fields being taught. All regressions include subfield fixed effects, and give same weight to each country. Standard errors are clustered at class level and reported in parentheses. * p < 0.10; ** p < 0.05; *** p < 0.01.

Table 6. Heterogeneous effects

	Physics + Chemistry + Biology + Earth Science					
	(1)	(2)	(3)	(4)	(5)	(6)
Major in fields taught	4.6463***	3.6094***	4.8522***	1.8133***	3.2709***	1.3705
	(0.3703)	(0.3884)	(0.5199)	(0.4084)	(0.5640)	(0.8647)
×Graduate degree	0.0104					
	(0.7594)					
×Number of majors in natural sciences: two		1.6479**				
		(0.8007)				
×Number of majors in natural sciences: three		4.4695***				
		(1.0100)				
×Teaching experience			-0.0167			
			(0.0316)			
×Girl				5.5927***		
				(0.5478)		
×Math Score: middle					0.6752	
					(0.5867)	
×Math Score: upper					3.0259***	
					(0.7014)	
×Physics						3.5350***
						(1.0053)
×Chemistry						5.7213***
						(1.0312)
×Biology						2.4731***
						(0.9133)
Observations	876,880	876,880	876,880	876,880	876,880	876,880
R-squared	0.920	0.920	0.920	0.920	0.920	0.920

Notes: All regressions include student-teacher fixed effects and subfields fixed effects, and give same weight to each country. Standard errors are clustered at class level and reported in parentheses. * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

Figure 1. Decomposition of mechanism

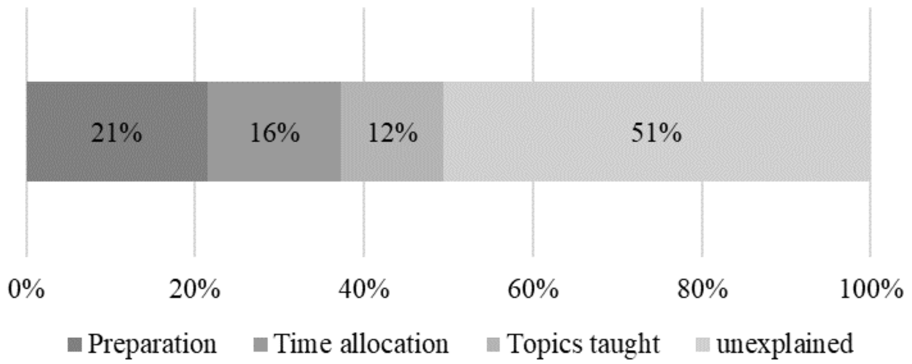

Table A1. Correlation coefficients between teachers' major fields and preparation status for teaching science topics

	Preparation			
	Physics	Chemistry	Biology	Earth Science
Major in Physics	0.26	0.13	-0.09	-0.03
Major in Chemistry	0.14	0.30	-0.01	-0.03
Major in Biology	-0.09	0.03	0.29	0.00
Major in Earth Science	-0.02	-0.03	0.03	0.16

Note: Number of observations is 876,880.

Table A2. Correlation coefficients between teachers' major fields and the time allocation for teaching

	Time allocation			
	Physics	Chemistry	Biology	Earth Science
Major in Physics	0.12	0.13	-0.06	-0.13
Major in Chemistry	0.06	0.17	-0.03	-0.14
Major in Biology	-0.13	-0.07	0.16	0.00
Major in Earth Science	-0.07	-0.03	-0.01	0.11

Note: Number of observations is 876,880.

Table A3. Correlation coefficients between teachers' major fields and the range of topics taught

	Range of topics taught			
	Physics	Chemistry	Biology	Earth Science
Major in Physics	0.04	0.07	0.01	-0.07
Major in Chemistry	0.01	0.03	-0.04	-0.12
Major in Biology	-0.08	-0.06	-0.03	-0.03
Major in Earth Science	-0.01	0.00	0.03	0.04

Note: Number of observations is 876,880.