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

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Abstract

We examine whether and how teachers' major fields of study affect students' achievement, exploiting the 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 the natural sciences improved students' achievement of subfields in the natural sciences corresponding to their own subfields of college majors. Teaching practices explain about half of the effect of teachers' major fields, and the majority of the effects through teaching practices is accounted for by teachers' preparation for teaching science topics. The results are robust to potential endogenous matching between students and teachers.

Keywords: Education, Teacher, Natural Science, College Major, Middle School, TIMSS
JEL classification: H75, I21, J24.

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1. Introduction

Science literacy is one of the most important determinants of success in labor markets. Altonji et al. (2012) and Kirkebøen et al. (2016) show that science, technology, engineering, and math (STEM) majors are positively associated with earnings in later life. Card and Payne (2021) show 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 find 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 the promotion of STEM education can be a policy measure to improve labor productivity and reduce the gender gap in wages.

To enhance students' science literacy, improving the quality of science teachers is one of the key measures. It is often argued that teacher quality have a significant impact on student learning outcomes (e.g., Hanushek and Rivkin 2010). However, since the prediction power of *observable* characteristics of teachers such as gender and teaching experience is generally limited (e.g., Hanushek and Rivkin 2006) and measurement of teacher quality is not straightforward, it is important for researchers and education administrators to find observable characteristics of teachers associated with the teacher quality in order to achieve optimal recruitment and assignment of highly qualified teachers.

Many researchers have studied the relationship between the teachers' subject-related degrees and knowledge and students' achievement as another observable predictor of teacher quality. To examine this relationship, they use various information such as major fields (e.g., 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 (e.g., Backes et al. 2018; Harris and Sass 2011), and more direct measures of a teacher's knowledge level include test scores and GPA of teachers (e.g., 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). In a review by Coenen et al. (2018), it is argued that teachers' subject-related degrees and knowledge, particularly for mathematics and science, are positively associated to students' academic performance.[2] Although some of the existing studies find positive association between them, little is known about the mechanisms how teachers' subject-related degrees and knowledge affect students' academic performance.

This study examines whether and how teachers' major fields affect students' achievement. Contrast to the previous studies focusing on the relationship between teachers' major fields and students' academic achievement in 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 natural science 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' major fields in natural science. Within-student variation across subfields enables us to estimate the effects of teacher's college major controlling student fixed effects *specific to natural science.* In addition, we investigate the primary channels through which these effects are derived. This examination of the mechanism behind the effect of teachers' major fields in natural science is one of our contributions.

In the estimation of the causal effects of teachers' major fields, it is necessary to consider potential biases due to endogenous matching between teachers and students. In the ideal case, students are randomly assigned to teachers across and within schools. However, assignments are rarely random because of school choice and optimal classroom formation (e.g., Clotfelter et al. 2006; Bonesrønning et al. 2005). For our research question, if unobserved characteristics are associated with both teachers' major fields and students' science test scores, the estimates of the effect of teachers' major fields will

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[2] Several studies find 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).

be biased. A typical strategy for this is to control students' fixed effects by taking within-student, cross-subject differences (e.g., 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 of both students and teachers when students are taught different subjects by the same teacher. However, this may not resolve the issue when different teachers teach each subject to a student and when teacher assignment is based on students' unobserved characteristics. We address this issue by restricting our sample to students taught by a science teacher who is 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 the subfields, the cross-subfields differencing identifies the effects of teachers' major fields in natural science on students' academic achievements by eliminating student-teacher fixed effects.

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] It should be noted that teachers who majored in a certain field in natural science would be more likely to improve not only the achievement of students in the field but also in other

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[3] A recent working paper, Sancassani (2021), employs similar identification strategy with the TIMSS data to account for student fixed effects by exploiting the variation within students across subfields in science. Since the main focus of his paper is to examine the effect of teacher characteristics (including subfields in science) on students' science achievement, he restricted the sample to students from countries where the subfields in science are taught by *different* teachers. Contrary, the main focus of our paper is to identify the effects of subfields in natural science of teacher major fields and its mechanism *controlling student-teacher fixed effects* by restricting our samples to students taught by *same* teachers. Although our paper is complement to his paper, the first draft of our paper was written in November 2020 without knowing his paper.

fields. Because of the spillover effects of teachers' major fields, the estimates here are considered as lower bounds.

To understand the mechanisms of 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, to allocate more time, and to teach a broader range in the subfields that corresponded to the major field. In addition, we conduct an analysis to examine the extent to which these teaching practices explain the effects of teachers' major fields. We find that the degree of preparation to teach science topics explains about 22% of the effect of teacher' major fields, which is the largest ratio among other channels such as time allocation and range of teaching topics. This result suggests that teachers' major fields in natural science have positive effects on students' academic outcomes through improving the quality of their preparation for teaching. Furthermore, we find that there is about 50% of the effect that cannot be explained, implying that the unobservable quality of teachers associated with their major fields remains to play an important role in improving the academic achievement of students. We also find heterogeneity in the effects of teachers' major fields: the positive effect is stronger for students taught by teachers with a greater number of major fields, female student, and students with higher ability.

The remainder of this paper is organized as follows. In Section 2, we discuss our empirical strategy. In Section 3, we explain our data and report the summary statistics. In Section 4, we present the main results of the effects of teachers' subfield major. Section 5 discusses potential mechanism behind the effects. Section 6 present heterogenous effects. Section 7 concludes.

2. Econometric Framework

To investigate the effect of teachers' major fields 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 subfields f in teacher j's class. $Major_{fj}$ is an indicator that represents whether the teacher's major fields in natural science and the subfields of the student's test score are matched and thus β is the coefficient of our main interest. δ_f is subfield fixed effects. η_{ij} is 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 show the results by the ordinary least squares estimation without the student-teacher fixed effects as well.

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 to teachers within a school based on students' subfield specific unobservables. For example, if students more able in physics than other subfield subjects are systematically assigned science teachers who majored in physics, then the estimates are biased. We address this issue by restricting our sample to small schools with only one class in the grade where it is unlikely to have multiple science teachers in the grade, to confirm the robustness of the results against potential endogenous matching between students and teachers based on students' subfield specific unobservables. Standard errors are 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 are information of middle-school students taken from the TIMSS survey for 2003, 2007, and 2011.[4] The TIMSS is an international survey conducted every four years

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

that measures the mathematics and science achievement of fourth- and eighth-grade students as well as students', homes', teachers', schools', and curricular backgrounds in participating countries and regions globally. For example, in the 5th survey conducted in 2011, 608,641 students, 49,429 teachers, and 19,612 school principals from 63 countries participated.

Each student's test scores in each subfield in science (i.e., physics, chemistry, biology, and earth science) are included as five plausible values (hereafter, call it PVs) in the TIMSS dataset.[5] PVs are generated by exploiting the item response theory method based on the results of the tests and questionnaires where the mean of the national average scores to 500 and the standard deviation to 100 for all countries participated in TIMSS 1995.[6] In all estimations, we use "student senate weight" included the dataset that is a rescaling of the student sampling weight to give same weight to each country because we use student samples taken from many countries.[7] In addition, we estimate the models using each of the five PVs separately and then report the average of the five estimates.[8]

In this study, we remove samples of students taught by more than one science teacher from our analysis. This is because when multiple teachers teach science classes, sorting between students and teachers can occur across subfields, causing bias potentially in the estimation. The size of pooled samples from the TIMSS of 2003, 2007, and 2011 is 513,295 excluding students who cannot be linked to their science teachers and who had multiple science teachers. We drop samples with missing values for any variable used in the estimation listed in Table 1 below. 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 and areas worldwide. To estimate the student-teacher fixed effects model

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[5] Samples are 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 the students who participated in the survey took the same test.

[6] PVs are multiple imputation 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), which use international survey data such as PISA and PIAAC, conduct weighted analyses so that the weights for each country are the same.

[8] We use the estimation Stata command "pv" written by Macdonald (2019).

that relies on a comparison of within-student, cross subfields in science, we pool student data from the four subfields.

[Table 1]

Table 1 reports the descriptive statistics of variables: students' academic achievement, teachers' major fields, teaching practices, school resources, and demographics. As shown in Table 1, the fraction that teachers' major field matches a subfield of science test scores (i.e., the mean of $Major_{fj}$) is 31.6 percent.[9] 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 fields of the four, the result of 31.7 percent means that, on average, science teachers majored in more than one subfield but less than two subfields. In terms of each field, the fraction of teachers majoring biology is relatively higher and earth science is very lower than the other two subfields.[10] In terms of the number of fields that teachers majored in, the percentage of teachers who majored in only one field is the highest at 41%, while the percentage of teachers who majored in all four fields is the lowest at 6.7%.

On student academic outcomes, the mean of students test scores is 471 and the standard deviation is 116 when all subfield test scores are included. There is almost no difference in the score distribution across subfield.[11]

TIMSS also contain information about teaching practices in each subfield. We use them to investigate the relation 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

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[9] 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.

[10] 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.

[11] While the TIMSS 2011 and 2007 include 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 we exclude the samples of TIMSS 2003.

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 from “Not applicable”, “Very well prepared”, “Somewhat prepared”, and “Not well prepared”. When a topic is not in the eighth-grade curriculum or when teachers are not responsible for teaching the topics, 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 per each subfield is used as the indicator of teachers’ preparation to teach science topics.[12] As shown in Table 1, the mean of teachers’ preparation scale is 2.56 when all subfields are included. This means that the readiness of teachers to teach science topics is somewhere between “Very well prepared” and “Somewhat prepared” on average. Focusing on each subfield, while teachers are relatively prepared well in chemistry, they are not in earth science. Furthermore, Table A1 showing the correlation coefficients between teachers’ major fields and the preparation status for teaching science topics indicates that the subfields corresponding to the teachers’ major fields are better prepared 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 the percentage for each subfield so that the total is 100 percent.[13] As shown in Table 1, the total average of the four subfields is about 92 percent, which indicates that these four are the main areas taught by science teachers. Focusing on each subfield, teachers spend

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[12] 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 the items in each subfield are as follows: In the order of the 2011, 2007, and 2003 TIMSS survey, 7, 7 and 5 in biology; 4, 5, and 5 in chemistry; 5, 6, and 5 in Physics; 4, 5, and 3 in earth science. An example of the items for biology is “Major organs and organ systems in humans and other organisms (structure/function, life processes that maintain stable bodily conditions) ”.

[13] While the TIMSS 2011 and 2007 have five science subfields in this question: biology, physics, chemistry, earth science, and others, the TIMSS 2003 have six: life science, physics, chemistry, earth science, environmental science, and others. We regard the answer in life science area in the TIMSS 2003 as the answer in the biology area.

their teaching time less on earth science than others.[14] Furthermore, Table A2 showing the correlation coefficients between teachers' major fields and teaching time allocation indicates that a little more time is spent on the subfields corresponding to the teachers' major fields compared to other subfields.

Finally, we look at the range of topics taught in each subfield by using the following question: "Choose the response that best describes when the students in your class have been taught each topic."[15] This question has many items that describe the main topics addressed by the TIMSS science test. If a teacher chose "Mostly taught before this year" or "Mostly taught this year", we assume that he or she had already taught the topic. As shown in Table 1, the mean of the percentage of the range of topics being taught is 67.5 percent. Focusing on each subfield, the percentage of earth science topics is 59.1 percent, which is lower than the approximately 70 percent of others. Furthermore, Table A3 showing the correlation coefficients between teachers' major fields and the range of topics being taught indicates that there is little correlation between them. This result may be because the teaching content is regulated by the national and school curriculum and teachers do not have much discretion on what to teach.

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

4. Results

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[14] 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 section of robustness check, we present results restricting to teacher sample those who teaches all subfields in science in a year and show that our results are robust.

[15] 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 taught by half 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 2011, 2007, and 2003 TIMSS survey, 7, 14 and 12 in biology; 4, 8, and 8 in chemistry; 5, 10, and 10 in Physics; 4, 14, and 11 in earth science.

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

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 test subjects of students. We report the results for four specifications in the column order: (1) including year fixed effects, subfields 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’ major fields 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, means that the subfield score of students taught by teachers who majored that subfield in college is higher by 0.05 standard deviation than that of those who are taught by teachers without college major of that subfield.

Column (4) presents an estimation result with student-teacher fixed effects. The coefficient of the teachers’ major fields dummy is positive and statistically significant. The estimated coefficient, 4.6485, is slightly lower than the estimate in column (3), suggesting that the estimates without controlling student-teacher fixed effects may be biased upward due to 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 major, 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 not only students’ achievement in physics but also the achievement of the other subfields in science. If these spillover effects exist, our estimates can be considered to present a lower bound of the effects of teachers’ major fields.

4.2. Robustness

The student-teacher fixed effects model identifies the effects of teachers' major fields if the matching between teachers and students are orthogonal to 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” 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 to schools or teachers based on students’ *subfields-specific* unobservables (“comparative ability”). For example, in the cases that a student who is better at physics than other subfields selects a school with high shares of science teachers who majored in physics, or 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 mechanism 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, we present results with the sample restricting to those who are taught by teachers who teach all four subfields spending instructional time of at least 10% and 20% to eliminate schools or teachers that specialize in a particular subfield.[16]

First, we restrict the sample to students living in small municipalities with a population of less than 15,000 to confirm whether there are any sorting effects between schools. This is because in smaller municipalities, there are fewer schools, and it is unlikely that there are schools that specialize in a particular subfield in science. The result of column (1) of Table 3 shows that the estimated effect is almost the same as the results in column (4) of Table 2. This result suggests that the potential sorting of students into schools based on comparative ability across subfields in natural science is not a serious concern in our sample.

Second, we restrict the sample to students who are in schools with only one class in the grade, where it seems unlikely that multiple science teachers teach one grade.[17] Column (2) of Table 3 reports the estimation result with the restricted samples. The coefficient is 3.5778, which is slightly lower than the estimate in column (4) of Table 2, suggesting a positive correlation between teachers' major fields and unobservable determinants of student achievement in subfield within a school. However, the estimate in column (2) of Table 3 remains statistically significant, suggesting that our result of the positive effect of college major in column (4) of Table 2 is robust for possible sorting of students to teachers within a school.

Third, we restrict the sample to those in which the teachers' instructional time share is at least 10% and 20% in each subfield to eliminate schools or teachers that specialize in a particular subfield. Column (3) and (4) of Table 3 reports that the coefficients are positive but smaller than the estimate in column (4) of Table 2. The results can be interpreted in at least two ways. One is due to student

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[16] The robustness check here uses the similar approach as in Bietenbeck et al. (2018).

[17] 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.

sorting: a group of students who were originally good at certain subfields are placed with a teacher who majored in the corresponded fields and have a large share of teaching hours in the subfields, caused an upward bias. The other interpretation is due to the loss of the part of the effect of the teachers' major fields. Teachers who majored a field in natural science tend to increase their instructional time share in the subfields corresponding to their major field, resulting in relatively higher student performance in the other subfields. Although the results of column (3) and (4) of Table 3 could include either interpretation, the coefficients on major in fields taught remains positive and statistically significant suggesting the robustness of our result in column (4) of Table 2 to potential sorting of students to schools and teachers. In the next section, we explore potential mechanisms accounting for this positive effect of teachers' college major.

5. Mechanism

To explain the positive effects of teachers who majored in natural science fields on students' academic achievement in the corresponding subfields, we analyze the relationship between science teachers' major fields and their teaching practices. Recent studies show that some teaching practices have a substantial impact on educational outcomes (e.g., Schwerdt and Wuppermann 2011; Van Klaveren 2011; Bietenbeck 2014; Lavy 2016; Tanaka and Ishizaki 2018; Motegi and Oikawa 2019). It is natural to think that differences in teachers' major fields may cause differences in their knowledge and in their teaching practices, which in turn affect students' academic achievement.

Understanding the mechanisms of the effects of teacher's major fields can be useful in policy making and school administration. It sheds light on more practical and accessible ways of improving student outcomes. For example, if a teacher does not have majors in the subfields of science that he or she is responsible for, the principal would assign another teacher with them. If such teacher arrangement is not feasible, 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. In addition, when hiring teachers, it will be important to make sure that candidates have majors in field related to the subjects they will be responsible for.

To investigate the mechanism of the effect of teachers' major from teacher's 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) range of science topics being taught. We investigate whether the teaching practices change depending on the teachers' major fields by estimating the following regression model (2):

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

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

[Table 4]

Table 4 presents the estimated coefficients of α^{k}. These results show that teachers tend to prepare well for teaching, spend more time, and teach a broader range of topics in the subfields that are corresponding to their major fields. Overall, there is a tendency that teachers put more efforts in the subfields that are corresponding 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).

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

The coefficient ζ represents the effect of teachers' major fields that is not explained by the observed change in the teaching practices. As a result, the ratio of the effect of the teachers' major fields explained by the combined changes in the observed change in the teaching practices is given by $1 - \zeta$

/ β. The ratio of the effect of the teachers' major fields attributable to the kth teaching practice can then be calculated by $\theta^k \alpha^k / \beta$.[18]

[Table 5]

Table 5 shows the estimation results in Eq. (3). It suggests that these three teaching practices are positively related to students' academic achievement (column (2) to (5) in Table 5). The coefficient of major in fields being taught in column (5) is 2.3526, which is smaller than the coefficient of that in column (1). This result suggests that the positive effect of teachers' major fields can be interpreted through the mechanisms of the three teaching practices, but the majority 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 a 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 was through the mechanisms of preparation, time allocation, and instructional coverage, respectively. Even after considering teaching practice, a half of the positive effect of teachers' college major remains unexplained.[19] These results are largely consistent with the findings in the literature where 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, but the effects may differ across

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[18] Note that if there is an unobserved mechanism that correlates with the observed mechanisms, θ^k might be biased. Therefore, interpretation of the estimation results should be carefully done.

[19] 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 sorting of students based on students' subfields specific unobservables within schools. 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.

teacher and school characteristics such as teachers' qualifications and experiences, and schools' instructional materials and science equipment. We estimate the Eq. (1) with interaction terms between teachers' major fields being taught and factors that may cause heterogeneity of the effects.

[Table 6]

Firstly, to explore whether 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 of teachers' major fields is smaller for those with a master's degree, but that the difference is not statistically significant. This implies that to improve student science achievement, science teachers need to have a degree in the subfields that is acquired at the bachelor's level, but not to the depth of it at the master's level.

To explore whether having wider range of major fields increases the effect, we add the interaction term between "Major in fields taught" and the number of teachers' major fields. 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 of their major fields on student achievements by 0.016 and 0.045 standard deviations, respectively. The result suggests that science teachers who have broader major fields tend to improve student achievement more.[20]

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' major fields. The effect seems

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[20] 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.

smaller for those with longer teaching experience, but the difference is not statistically significant.[21] The result implies that lack of 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 student characteristics of gender and ability by adding the interaction terms. Using math test scores as a proxy measure of student ability, we divided the students into three groups: upper, middle, and lower ability. The results show that the effect of teachers' major fields is larger for female students (Column (4)) and for students with higher ability (Column (5)).

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

7. Conclusion

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

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

We find that eighth-grade students taught by teachers with majors in natural science field improve their achievement in subfields of science by 0.05 standard deviations that are corresponding to teachers' major fields than those taught by teachers without it. Exploring the potential mechanisms through which teachers' major fields 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 corresponding to their major fields. These mechanisms of teaching practices explain roughly half of the effects of teachers' major fields. In particular, improving the quality of their preparation for teaching explains about 21 percent of the effects. About 50 percent of the mechanisms of the effect of teachers' major fields cannot be explained by observable teaching practices, which may suggest that the unobservable quality of teachers associated with their major fields plays an important role in improving the academic achievement of students.

Our findings make several contributions to the literature and have some 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 in science using a cross-subfields analysis with student-teacher fixed effects. Second, we provide evidence of the mechanism that drives the effects of teachers' major fields: teaching practices. Third, we provide evidence of the heterogeneity in the effects of teachers' majors fields in natural science across characteristics of teachers and schools. These findings shed light on educational policies designed to improve student outcomes in science. For example, our findings suggest that assigning science teachers to teach subfields that corresponding to their major fields is beneficial. One way to compensate for teachers without major in natural science fields could be to provide them with training opportunities to acquire expertise and pedagogy in natural science and to 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

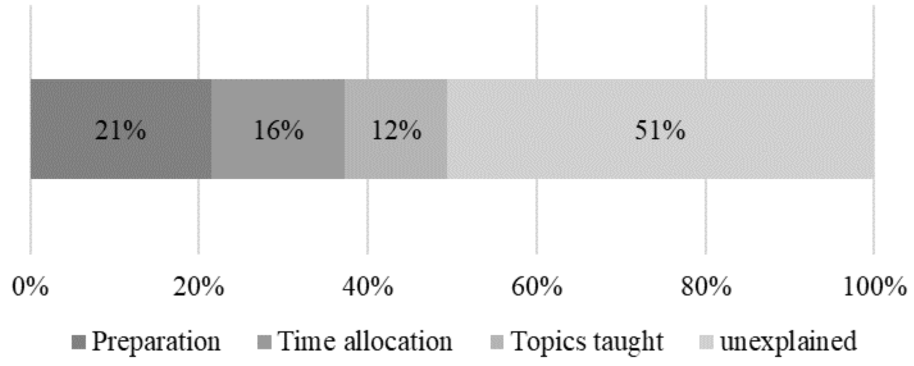

Table A1. Correlation coefficients between teachers' major fields and preparation status for teaching science topics

	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.