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Effects of Teacher Professional Development and Science Classroom Learning Environment on Students' Science Achievement

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Abstract
Science classroom learning environment (CLE) and science teacher professional development (PD) are two important factors in students' science learning. However, the nature of the science CLE and school-level PD that promotes students' science achievement remains unclear. Using the Program for International Student Assessment (PISA) 2015 data, this study aims to explore the multi-level relationships between student-reported CLE, school-level teacher PD, and the possible interaction effects between the two on students' science achievement. Since sample students were nested within schools, two-level hierarchical linear models (HLM) were used to analyze the data. Results indicated that science CLE factors, including direct instruction, adaption of instruction, and disciplinary climate, had significantly positive relationships with students' science achievement, while inquiry-based science teaching and learning practices and perceived feedback had significantly negative relationships with students' science achievement. Moreover, these relationships varied significantly between schools. For school-level PD factors, the proportion of PD in school science and proportion of teachers attending PD within 12 months had significantly positive relationships with students' average science achievement between schools. More importantly, a significant cross-level interaction effect was found between PD requirements and disciplinary climate. Implications for creating science CLEs to promote students' science learning, including implementing science teacher PD through a school-level approach and modifying PD based on CLE contextual factors, are also provided.

Keywords Learning environment · Professional development · Learning outcomes · Science achievement

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Introduction

Science education reforms across K-12 have become intensifying worldwide because of today's pressing global challenges (National Research Council [NRC] 2000). The aim of the reforms is to foster not only students' science understanding but also their overall science literacy, including how to apply science knowledge to solve problems (European Commission 2011; Organization for Economic Cooperation and Development [OECD] 2017). But how can science literacy be best cultivated among students in science classrooms? Teachers and their classroom practices are considered as a major conduit for the transference of reform efforts into student learning outcomes. As such, it is of critical importance to prepare teachers for the challenge of improving students' science literacy. Teacher professional development (PD) may increase teachers' knowledge, change their attitudes and beliefs toward teaching, thereby improve their classroom practice, which in turn results in fostering student learning outcomes (Desimone 2009). Furthermore, student classroom learning environment (CLE) in science may also play a significant role in improving students' science literacy. However, little is known about the relationship between science-specific CLE and student science learning, especially the possible interaction between PD and CLE on student science literacy. The *Program for International Student Assessment* (PISA) assesses 15-year-old students' science literacy as the use of scientific knowledge to identify questions, acquire new knowledge, explain scientific phenomena, and draw evidence-based conclusions about science-related issues, in over 70 countries (OECD 2017). This study explored the relationships among PD, CLE, and student science literacy by using the data of PISA 2015.

Classroom Learning Environment

Learning environment refers to the "social, psychological, and pedagogical contexts in which learning occurs and which affect student achievement and attitudes" (Fraser 1998, p. 3). Previous studies have established that CLE is a significant predictor of students' academic achievement (Aluri and Fraser 2019; Fraser and Kahle 2007). However, features of effective CLEs that are positively associated with students' academic achievement vary across studies (Allen and Fraser 2007; Moos 1979; Walberg and Anderson 1968). For example, using the same instrument, Allen and Fraser (2007) found that teacher support and involvement have no relationship with students' science scores. In contrast, Aluri and Fraser (2019) found that teacher support and involvement significantly predicted students' math scores. Giving the nature of science learning, an effective science CLE might differ from an effective CLE in other disciplines. Consequently, commonly measured CLE domains might not adequately represent an effective science CLE, for example, science inquiry might be a CLE component that is important only in science but not in other disciplines. Therefore, empirical research that directly addresses the disciplinary features of effective CLEs is essential.

PISA 2015 defined seven factors of science CLE: disciplinary climate, teacher support, teacher-directed science instruction, perceived feedback, adaption of instruction, instrumental motivation, and inquiry-based science teaching and learning practices (OECD 2017). A number of studies have provided evidence on the relationships between the above science CLE variables and student science achievement. In particular, most studies established that disciplinary climate, teacher support, direct instruction, and adaption of instruction are positively associated with students' science achievement, such as motivation, engagement, and test scores (Cheema and Kitsantas 2014; Chi et al. 2018; Dietrich et al. 2015; Pitzer and Skinner

2017). Some studies indicated negative associations between science achievement and perceived feedback and science inquiry-based practices (Lau and Lam 2017; Sjøberg 2018).

However, the relationships between the science CLE variables and students' science achievement have not been fully examined. Previous studies focused only on a few variables, and they did not consider them from a science CLE perspective, so the nature of the science CLE that promotes students' science achievement remains underexplored. Further, because school-level and classroom-level learning environments are independent (Allen and Fraser 2007; Taylor and Fraser 2013), it is reasonable to hypothesize that the relationships between science CLE factors and student science achievement may vary across schools. For example, since student characteristics, such as performance and attitudes, vary by school type (Benson and Seastrom 1991), the extent to which students require teacher support (one of the CLE domains) might differ between public and private schools. Studies exploring CLE and academic achievement usually only consider within-school variations but not between-school variations (Oser and Fraser 2015). Thus, it is worthy to investigate the relationships between science CLE variables and student science achievement at school level.

Professional Development

PD refers to the activities designed to consolidate teachers' professional knowledge, skills, and attitudes, for the purpose of improving student learning (van Driel et al. 2012). A number of studies have examined features of effective PD. Two widely accepted core features of high-quality PD are content focus and sustained duration (Kennedy 2016; Cohen and Hill 2000; Desimone 2009). Content focus refers to the increase of teachers' expertise related to different knowledge domains of teaching, and sustained duration refers to the total contact time and frequency of teachers' engagement within the PD (Fischer et al. 2018). The authors (2018, 2020) determined that PD duration had a positive and significant relationship with student learning. Other core features, including opportunities for active learning and supportive collaboration, have also been identified in previous studies (Darling-Hammond et al. 2017). Furthermore, students' achievement directly related to the type of PD that their teachers experienced (Cohen and Hill 2000; Johnson et al. 2007), and to attain significant improvements in student achievement, PD should be established at the school-level (McChesney 1998; Johnson et al. 2007). Whole-school, collaborative, and sustained PD programs are necessary for teachers to improve their instructional practices (Hart and Lee 2003; Johnson et al. 2007). Thus, the relationship between school-level science PD implementation and student science achievement is worth investigating.

PISA 2015 measured science teachers' PD by including several questions in the teacher questionnaire (OECD 2017). The questions measured PD duration, such as whether teachers participated in any PD activities within 12 months, content of PD, such as the proportion of PD activities related to school science (limited to subjects or courses that are taught in school), and type of PD, such as mentoring and/or peer observation and coaching, and reading professional literature. The teacher data in PISA 2015 can be linked to school-level data; thus, school-level science teacher PD information can be determined, such as the proportion of science teachers required to participate in PD and the average proportion of PD content related to broad science and school science. Thus, it is possible to explore the relationships between science PD variables and student science achievement at school level.

Conceptual Framework

This study is underpinned by field theory (Lewin 1936), which has been a widely accepted psychological theory utilized in educational environment research for decades. Field theory recognizes that the total field or environment of the individual and its interaction with personal characteristics influence a person's behavior. Studies have built upon field theory and have investigated the positive association between learning environments and students' learning performance (Walberg and Anderson 1968; Fraser and Fisher 1983). Additionally, given that the teacher plays an integral role in students' learning, teachers' performance is a crucial factor that can also be regarded as part of the learning environment in predicting students' performance (Walberg 1969). This study's conceptual framework is depicted in Fig. 1.

Furthermore, because most CLE variables are created and managed by teachers (Aldridge et al. 1999; Moos 1979; OECD 2017), it is reasonable to hypothesize that interactions between science CLE and science PD may relate to student science achievement. Teachers who experience different types of PD might cultivate different CLEs, which could differentially impact student achievement. Similarly, the relationships between teacher PD and student academic achievement might also vary based on the CLE. No empirical study explores the possible interaction between CLE and PD and how the interaction may influence student academic achievement. Thus, the purpose of this study was to fill the above research gap by exploring the relationships between student science achievement and CLE, PD, and their possible interaction. Specifically, the research questions for this study are:

(1) Is there a statistically significant relationship between student science achievement and science CLE variables?
(2) Is there a statistically significant relationship between student science achievement and school-level science teacher PD?

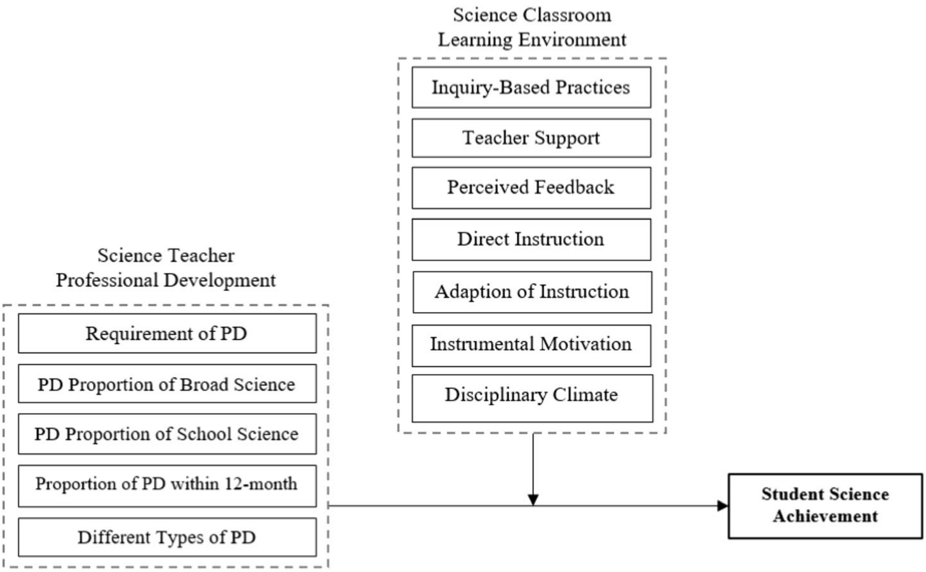

Fig. 1 Conceptual framework of the interaction effects

(3) Is there a statistically significant relationship between student science achievement and the interactions between science teacher PD and CLE?

Method

Data and Sample

PISA 2015 used a two-stage sampling method (OECD 2017). The first-stage sampling units were individual schools that included 15-year-old students at the time of the assessment. The second-stage sampling units were students within the sampled schools. Students were randomly selected within each school with equal probability. Overall, approximately 540,000 students completed the assessment, representing about 29 million 15-year-olds in schools of the 72 participating countries. The current study used the USA subsample, which originally had 5712 students nested within 173 schools. After listwise deletion of missing data, 3903 students nested within 137 schools (79%) remained. Data from the three questionnaires were applied: student-level control variables and student-reported science CLE variables were obtained from the student questionnaire; school-level control variables were obtained from the school questionnaire; and science teacher PD variables were obtained from the teacher questionnaire.

Variables

Dependent Variable Student science achievement in terms of science performance was the dependent variable in this study. In PISA 2015, student science performance was measured through different subsets of items instead of all items, and the scores were imputed based on the item response theory (IRT) model, which generated 10 plausible values (PV1SCIE to PV10SCIE) to represent student science performance. To provide a more precise estimation, a composite measure was generated by the plausible value method using all 10 science plausible values to represent students' overall science performance.

Independent Variables Science CLE and science teacher PD were two focused independent variables in this study. In total, seven CLE variables and five PD variables were examined. Specifically, CLE variables obtained from PISA 2015 student questionnaires. The CLE variables were derived measures scaled by using the IRT model, and reliability for each variable was established. PD variables obtained from PISA 2015 teacher questionnaires, and all the variables were aggregated to school level to represent average school science teacher PD.

Control Variables Student gender; economic, social, and cultural status; and science self-efficacy were selected as student-level control variables in the current study. School type and class size were selected as school-level control variables. Names and descriptions of all above variables are presented in Table 1.

Analytical Method

The hierarchical linear modeling (HLM) was used to analyze the data because students were nested within schools, and student weight variable (W_FSTUWT) was used during the

Table 1 Variable names and descriptions of the focused independent variables

Independent variables	Variable name	Variable name in PISA	Description (OECD 2017)
Science CLEs (student level)	Inquiry-based science teaching and learning	IBTEACH	Frequency of inquiry-based activities in science class
	Directed instruction	TDTEACH	Frequency of direct instruction to teach science content
	Teacher support	TEACHSUP	Frequency of teacher supports student learning
	Perceived feedback	PERFEED	Frequency of providing feedback and advice to students
	Adaption of instruction	ADINST	Frequency of adapting instruction according to students' needs
	Disciplinary climate	DISCLISCI	The extent to which students miss learning opportunities due to disruptive behavior in the classroom
	Instrumental motivation	INSTSCIE	Students' science learning motivation with respect to practical purposes (i.e., getting a job)
Science teacher PDs (school level)	PD participation requirements	TC021Q01NA	Proportion of science teachers required to participate in PD activities
	Proportion of broad science	TC030Q01NA	Proportion of PD in teaching broad science. Broad science refers to all topics covered in academic or popular science and technology
	Proportion of PD in school science	TC030Q02NA	Proportion of PD in teaching school science. School science is limited to subjects or courses that are taught in school
	Proportion of PD within 12 months	PROPDT20	Proportion of science teacher participation in any PD activity within 12 months
	Different types of PD within 12 months	TC020	Average number of different types of PD activity that science teacher attended within 12 months

analysis by considering the two-stage sampling method. This study also used the IEA International Database Analyzer (IDB Analyzer) for descriptive statistics and correlations related to the plausible values, followed by HLM 7.3 to explore the multi-level correlational relationships among the variables. Two-level intercepts- and slopes-as-outcomes model was conducted by using HLM to examine the correlational relationships between science CLE and student science performance (RQ1) and those between school-level science PD and student science performance (RQ2). Finally, a cross-level interaction model with both CLE and PD variables were tested to explore the possible interaction between CLE and PD, and the correlational relationship between interaction and student science performance (RQ3). The detailed HLM models mentioned above can be found in Appendix 1.

Results

Descriptive Statistics and Correlation

Descriptive statistics and correlations of CLEs, PDs, and science achievement are presented in Table 2. The results indicate that all of the hypothesized CLE and PD variables were significantly weak to moderately correlated with students' science achievement, except for the proportion of PD in school science. All significant correlations between the major independent factors had small magnitudes. The results suggest there was no collinearity between the hypothesized factors, and all the factors were independent.

For the school-level PD factors, the results indicate that 77.4% schools required all science teachers to participate in PD, and in 88.7% schools, all science teachers participated in PD within 12 months. On average, science teachers participated in around 4 out of 6 different types of PD within 12 months ($M = 3.97$, SD = 0.52), 25.09% of science teacher PD content was related to broad science ($M = 25.09$, SD = 12.23), and 26.74% of science teacher PD content was related to school science ($M = 26.74$, SD = 10.33). Furthermore, the intra-class correlation generated from the fully unconditional model was 0.174, which indicated that students' average science achievement varied between schools, and about 17.4% of the total variance in students' science achievement occurred between schools.

Science CLE and Students' Science Achievement

The relationships between the science learning environment factors and students' science achievement are presented under the Learning Environment Model (Table 3). When controlling for other factors, direct instruction and adaption of instruction had significant positive relationships with student science achievement ($\gamma = 10.94$, $p < .001$, and $\gamma = 10.44$, $p < .001$, respectively). The results indicated that students taught by science teachers who use direct instruction, adapt instruction according to students' needs, were more likely have better science achievement. One unit increase in the frequency of direct instruction and adaption instruction associated with 10.94 and 10.44 unit increase in students' science achievement, respectively. Furthermore, disciplinary climate also had a significant positive relationship with students' science achievement ($\gamma = 15.71$, $p < .001$), which indicated that students in classrooms with higher disciplinary climate tended to have higher science achievement. One unit increase in disciplinary climate was associated with a 15.71 unit increase in students' science achievement.

Table 2 Means, standard deviations, and correlations of CLEs, PDs, and science achievement

Variable	Mean	SD	Correlations												
			Broad PD	School PD	PD participate	PD types	Require PD	Inquiry practice	Direct instruction	Teacher support	Feed-back	Adapt instruction	Disciplinary climate	Instrument motivation	Science achievement
Broad PD	25.09	12.23	1.00												
School PD	26.74	10.33	0.28*	1.00											
PD participate	0.98	0.05	0.03**	0.10**	1.00										
PD types	3.96	0.52	−0.12**	−0.28**	−0.27**	1.00									
Require PD	0.95	0.10	−0.26**	−0.14**	0.00	0.01	1.00								
Inquiry practice	0.03	0.02	−0.03**	0.02*	0.01	−0.05**	0.03**	1.00							
Direct instruction	0.02	0.02	0.00	−0.04**	0.01	−0.02*	0.01	0.30**	1.00						
Teacher support	0.03	0.01	−0.01	0.01	0.02*	−0.04**	0.00	0.47**	0.44**	1.00					
Feedback	0.03	0.01	−0.02*	−0.01	0.00	−0.05**	0.04**	0.41**	0.43**	0.45**	1.00				
Adapt instruction	0.03	0.01	−0.01	0.01	0.04**	−0.03**	0.02*	0.35**	0.50**	0.56**	0.56**	1.00			
Disciplinary climate	0.03	0.01	0.04**	0.04**	0.06**	0.00	−0.06**	0.04**	0.19**	0.20**	0.09**	0.20**	1.00		
Instrumental motivation	0.02	0.01	−0.05**	−0.03**	0.03**	−0.02*	0.01	0.21**	0.15**	0.22**	0.16**	0.16**	0.07**	1.00	
Science achieve-ment	505.70	95.93	−0.02*	0.01	0.06**	0.06**	0.02*	−0.10**	0.13**	0.05**	−0.17**	0.08**	0.25**	0.02*	1.00

*$p < .05$, **$p < .01$, student $N = 5712$, school $N = 171$

Table 3 Science learning environment and students' science achievement

	Fully unconditional model γ (SE)	Control factors model γ (SE)	Learning environment model	
			Fixed effect γ (SE)	Random effect τ (SD)
Average science achievement	503.37** (3.83)	502.35** (3.11)	− 0.268 (0.219)	1052.50** (32.44)
Gender		7.43* (2.91)	14.98** (2.84)	
ESCS		23.74** (1.84)	22.56** (1.84)	55.43* (7.45)
Science self-efficacy		13.35** (1.41)	13.30** (1.19)	
Inquiry-based science teaching and learning			− 11.98** (1.73)	31.66* (5.63)
Directed instruction			10.94** (1.66)	33.62* (5.80)
Teacher support			2.52 (1.85)	
Perceived feedback			− 21.38** (1.57)	
Adaption of instruction			10.44** (1.86)	
Disciplinary climate			15.71** (1.61)	44.99** (6.71)
Instrumental motivation			− 0.63 (1.55)	
Additional variance explained by the model		11.26%	12.93%	

$^*p < .05$, $^{**}p < .01$, $^{***}p < .001$

Inquiry-based science practice and perceived feedback had significantly negative relationships with students' science achievement ($\gamma = -11.98$, $p < .001$, and $\gamma = -21.38$, $p < .001$, respectively). The results indicated that students in the classroom with more frequent inquiry-based practice and taught by teachers who provided feedback more frequently tended to have lower science achievement. One unit increase in inquiry-based science practice and perceived feedback associated with a 11.98 and 21.38 unit decrease in students' science achievement. Teacher support and instrumental motivation had no significant relationships with students' science achievement, above and beyond the impact of other factors in the model.

The science CLE factors together explained 12.93% of the variance on students' science achievement, and there was still a large amount of unexplained variance on students' average science achievement between schools. The variation in the relationships between science learning environment factors and students' science achievement between schools are presented in Table 3, under the Learning Environment Model Random Effect. The results indicated that the relationships between the three CLE variables, including inquiry-based science practice, direct instruction, and disciplinary climate, and student science achievement significantly varied between schools ($\tau = 31.66$, $\chi^2 = 163.47$, df = 133, $p < .05$; $\tau = 33.62$, $\chi^2 = 165.08$, df = 133, $p < .05$; and $\tau = 44.99$, $\chi^2 = 176.18$, df = 133, $p < .05$, respectively), while the relationships between other science CLE factors and students' science achievement did not vary between schools.

The relationships between gender, ESCS, students' science self-efficacy, and students' science achievement indicated that all of the identified control variables had statistically significant relationships with students' science achievement. Gender, ESCS, and students' science self-efficacy explained 11.26% of the variance on students' science achievement.

Science Teacher PD and Students' Science Achievement

The relationships between school-level PD factors and students' average science achievement are presented under the PD Model column in Table 4. When other variables were controlled, proportion of PD in school science and proportion of teachers attending PD activities within the last 12 months had significantly positive relationships with students' average science achievement ($\gamma = 0.53$, $p < .05$, and $\gamma = 107.16$, $p < .05$, respectively), which indicated that schools with science teachers attending more content-related PD specific to subjects or courses at schools, and schools with higher proportions of science teachers attending PD, tended to have higher average school science achievement. One unit increase in the percentage of school PD and science teachers who attend PD activity within 12 months was associated with 0.53 and 107 unit increase in students' average science achievement. However, other school-level PD variables had non-significant relationship with students' average science achievement. The above school-level PD variables together explained 4.83% of the variance on students' average science achievement between schools.

The relationships between school type, class size, and students' average science achievement indicated that both school type and class size had no significant relationships with students' average science achievement above and beyond the effect of gender, ESCS, students' science self-efficacy, and science learning environment factors. School type and class size together explained about 2.3% of the variance on students' average science achievement.

Table 4 Science teacher professional development and students' science achievement

		School-level control factors model γ (SE)	Professional development model γ (SE)
Dependent variable	Average science achievement	501.56** (3.30)	501.29** (3.21)
			15.06** (2.84)
	ESCS	22.43** (1.84)	22.49** (1.84)
	Science self-efficacy	13.28** (1.19)	13.20** (1.18)
	Inquiry-based science teaching and learning	− 11.99** (1.73)	− 12.12** (1.73)
	Directed instruction	10.96** (1.66)	10.98** (1.66)
	Teacher support	2.50 (1.85)	2.45 (1.85)
	Perceived feedback	− 21.37** (1.57)	− 21.34** (1.57)
	Adaption of instruction	10.45** (1.86)	10.51** (1.86)
	Disciplinary climate	15.73** (1.60)	15.77** (1.60)
	Instrumental motivation	− 0.62 (1.55)	− 0.57 (1.55)
Level-2 Variables	Class size	− 0.39 (0.65)	− 0.49 (0.63)
	School type	− 4.28 (6.28)	− 4.53 (5.33)
	Requirement of PD		13.59 (23.11)
	Proportion of PD in broad science		− 0.17 (0.25)
	Proportion of PD in school science		0.53* (0.25)
	PD activity within 12 months		107.16* (50.90)
	Different types of PD within 12 months		10.56 (6.81)
	Additional variance explained by the model	2.30%	4.83%

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Cross-Level Interaction Effect

Significant interaction between PD requirements and disciplinary climate was found in the cross-level interaction model. The results suggested that PD requirements had a significantly positive association on the relationship between disciplinary climate and students' science achievement ($\gamma = 11.97$, $p = .05$). To visualize the cross-level interaction effects, both disciplinary climate and PD requirements were then converted into categorical variables (one standard deviation below the mean as low level and one standard deviation above the mean as high level, see Fig. 2).

According to the graph on top, the relationship between disciplinary climate and students' science achievement varied according to science teacher PD requirements. Disciplinary climate and students' science achievement had significant positive relationships for both high and low PD requirement groups, but the positive relationship was stronger in the high PD

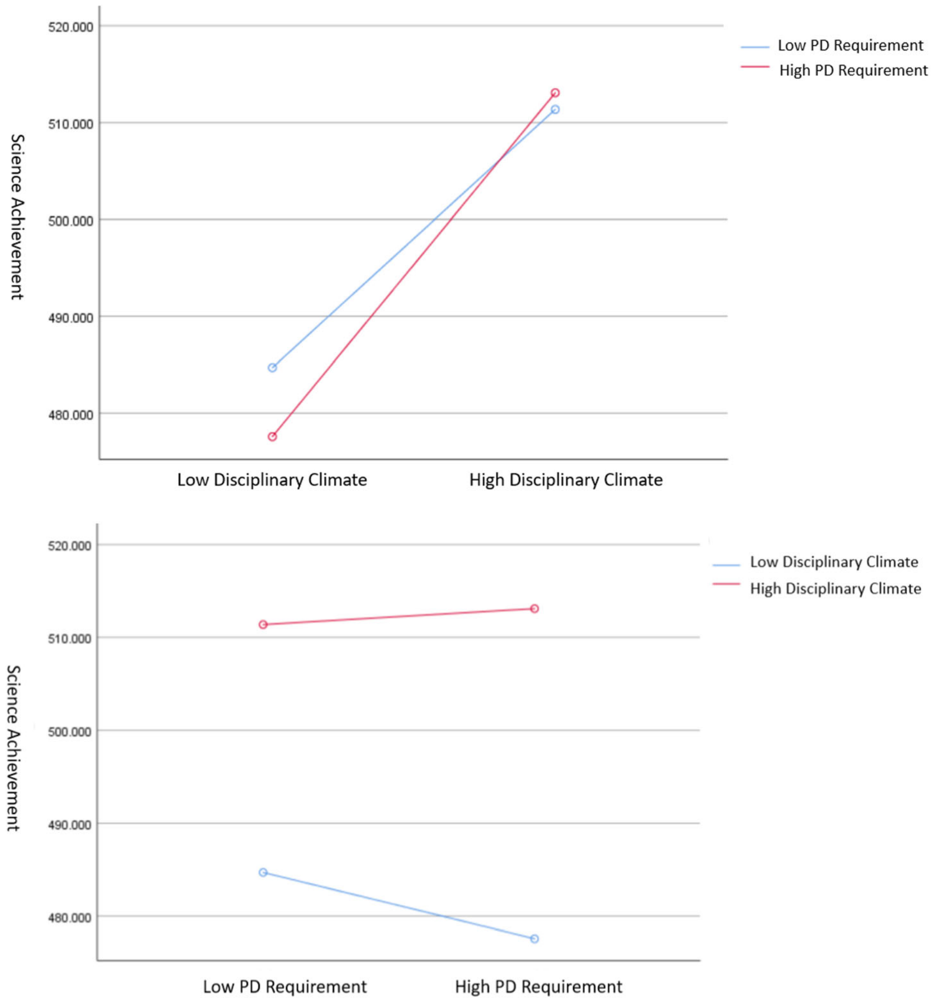

Fig. 2 Cross-level interaction effect between disciplinary climate and PD requirement

requirement group. The average science achievement for schools that do not require all science teachers to attend PD increases when the disciplinary climate increases. However, compared to schools that require all science teachers to attend PD, a sharper increase in science achievement can be seen.

Furthermore, the relationship between PD requirements and students' science achievement varied based on disciplinary climate. For schools with high student-reported disciplinary climate, students' science achievement had slightly increased with the requirements of science teacher PD activity. In contrast, for schools with low student-reported disciplinary climate, students' science achievement had a sharp decrease with the requirements of science teacher PD activity. The graphs show that science teacher PD might be required in schools with high disciplinary climate science classrooms rather than schools with low disciplinary climate science classrooms.

Discussion

Classroom Learning Environment and Student Science Performance

Several scales in measuring classroom environment have been established based on the findings of previous studies (Aldridge et al. 1999; Moos 1979; Walberg and Anderson 1968). Nevertheless, none of the existing literature points to specific standards of effective science CLEs. One of the major findings of this study is that it provides some insights on the features of science CLEs that promote students' science performance.

Consistent with prior studies (Cheema and Kitsantas 2014; Chi et al. 2018; Lau and Lam 2017), the current study found that disciplinary climate and direct instruction positively associated with student science performance. Adaption of instruction was another significant positive factor related to students' science performance. It seemed desirable for teachers to create a science CLE with a stronger disciplinary climate (e.g., stability and effectiveness of classroom rules), use more direct instruction (e.g., explaining scientific ideas and discuss students' questions), and adapt instruction according to students' needs (e.g., providing individual help and changing lesson structure when most students feel difficult to follow). Although teacher-centered learning (e.g., teacher explain scientific ideas) might benefit student test scores for a short term, it is unclear if teacher-centered learning would promote student development of science literacy in a long-term. More research is needed to clarify these relationships.

The insignificant relationship between teacher support and student science performance was inconsistent with the literature that encourages teacher support (Aluri and Fraser 2019; Dietrich et al. 2015; Fraser et al. 1996), but it aligned with Allen and Fraser's study (2007), which showed no relationship between teacher support and student science achievement. This might be due to different measures of teacher support between previous studies and PISA 2015, in which only the quantity of teacher support was assessed, such as "how often the teacher shows an interest in every student's learning" (OECD 2017). Dietrich et al. (2015) consider that teacher support shapes students' development in the classroom through their instruction and interactions with students, and both qualitative and quantitative questions should be asked to accurately determine teacher support in science classroom. Another possible explanation for the non-significant relationship might be that other CLE factors mediated the relationship between teacher support and student science performance. For example, adaption of instruction asks whether “the teacher provides individual help when a student has difficulties understanding a topic or a task,” which actually assesses teacher support according to students’ needs. It suggested that providing targeted support according to students’ needs might be more effective than providing general support. More work needs to be done to further investigate the possible mediation relationship, and teacher support questions should be clearer and more accurate to examine the above relationships. Similarly, mediation relationships might also exist between instrumental motivation and student science performance. Previous studies have indicated that student science learning motivation significantly predicts their science achievement (Fonseca et al. 2011; Karakolidis et al. 2019). However, instrumental motivation did not significantly relate to student science performance in our study, when taking other CLE factors into consideration. This finding also merits further investigation.

Perceived feedback and inquiry-based science practice were negatively related to student science performance, which were consistent with previous studies by using PISA data (Cairns and Areepattamannil 2019; Lau and Lam 2017; Sjøberg 2018). However, this should not be interpreted to suggest that teachers should cease providing feedback to students or implementing inquiry-based practice (Chi et al. 2018; Lau and Lam 2017; Sjøberg 2018). On one hand, research that used large-scale database, such as PISA, shows negative relationships between inquiry practice and student academic achievement, while quasi-experimental designs usually indicate positive relationships between the two variables (Margunayasa et al. 2019; Maxwell et al. 2015). Compared with large-scale database, the quality of inquiry practice in quasi-experimental studies can be ensured with guidance from researchers (Margunayasa et al. 2019; Maxwell et al. 2015). Without considering the design and quality of inquiry practice, the negative relationship between inquiry practice and student academic achievement might be biased. Furthermore, although inquiry-based science practice negatively related to student science performance, it showed positive relationship with student science learning motivation, interest, and self-efficacy, which might, in turn, promote student science performance (Sjøberg 2018).

On the other hand, previous studies showed that teachers’ feedback was often positively related to student science achievement (Burns et al. 2019; Van der Kleij et al. 2015). The reasons of the negative relationship found in this study might be two-fold. First, similar to inquiry practice discussed above, perceived feedback as measured in PISA 2015 might not represent quality classroom feedback given by teachers. Teachers’ feedback in previous studies was specific, e.g., feedback on student homework, while the perceived feedback in PISA 2015 was general, for example, “the teacher tells me how I can improve my performance.” Second, Burns et al. (2019) showed that two items in perceived feedback of PISA 2015 positively related to Australian students’ science achievement, and the results illustrated some clues that the other three items of perceived feedback in PISA 2015 might measure other properties. Thus, perceived feedback and inquiry-based science practice should still be considered as critical components of science CLE, but the quality of inquiry-based practice and the quality and specifics of feedback should not be assumed. Further investigation is necessary to explore best practice in effective inquiry-based science practice, along with specific quality teacher feedback and support, to improve student science performance.

Moreover, this study found that the relationships between student science performance and disciplinary climate, direct instruction, and inquiry-based science practice significantly varied among schools. To a certain extent, the study shed light on the conflicting results surrounding the relationships between inquiry-based science practice and student science performance. That is, although inquiry-based science practice negatively related to student science achievement (Lau and Lam 2017; Sjøberg 2018), this relationship may differ depending on school characteristics. For example, some studies suggested that inquiry-based practice promoted student science achievement in relatively small class sizes (Maxwell et al. 2015) and better disciplinary climates (Chi et al. 2018). Further investigation is necessary to explore the enactment of effective science inquiry by considering school-level factors, such as school type, climate, support, and average class size, among other factors.

Professional Development and Student Science Performance

Although previous studies have discussed the features of effective PD in general (Fischer et al. 2018; Johnson et al. 2007), specific insights on how to implement science teacher PD at the school-level are lacking. A major contribution of this study is that it considers science teacher PD from a school-level perspective.

Consistent with prior studies, this study pointed out that sustained duration and content focus remain two significant features of effective PD at the school-level in promoting student science performance (Authors 2018; Authors 2020; Cohen and Hill 2000; Desimone 2009). Regarding sustained duration, although the proportion of science teachers required to attend PD in school had no relationship with student average science performance, schools with higher proportion of science teachers attending PD activity within 12 months tended to have higher average school science performance. Thus, suggestions can be made for schools to require more science teachers to attend PD regularly to benefit student science performance.

Furthermore, research has established that content-focused PD is effective in promoting teaching practice by increasing teachers' knowledge domains (Fischer et al. 2018). However, previous studies did not make distinctions between school science and broad science content in such PD. It seems that promoting science teachers' understanding in broad science might benefit student science performance, but the findings of this study did not support it. Educators and researchers should consider whether the existing broad science PD is ineffective and how to improve the quality of broad science PD, to better support student science learning. It is reasonable to hypothesize that although broad science PD had no relationship with average science performance, it may promote student interest, motivation, and self-efficacy in science learning, which, in the long term, may lead to changes in student science performance, and persistence in science pathways and careers (Eccles 2011; Hazari et al. 2010).

Interaction Between CLE and PD

The significant interaction effect between PD participation and disciplinary climate on student science performance offered new perspectives for promoting student science performance. Numerous studies have indicated that PD participation promotes teacher knowledge and practice and thereby improving student academic achievement (Fischer et al. 2018; Meissel et al. 2016). It is necessary to require teachers to participate in PD activities to benefit student learning. However, this study illustrated that science teacher PD requirements might be considered together with disciplinary climate, because PD requirements positively related to student science performance in schools with high science classroom disciplinary climate, but not in schools with low science classroom disciplinary climate.

A possible reason for this significant interaction might be that science teachers in classrooms with lower disciplinary climate might spend more time on classroom management and subsequently less time in implementing the gains of PD, such as reform-based instruction (Avraamidou 2017). When teachers are discouraged in implementing such strategies because of more concerns about disciplinary climate or lack of time to fully apply the practice, teaching quality becomes an issue. This might explain the results that students whose teachers participated less PD performed better than those whose teachers participated more PD in low disciplinary climate classrooms, considering that teachers with less PD are more likely to insist on their traditional teaching practice compared with teachers with more PD.

Furthermore, the designers of PD might consider the unique challenges that teachers might experience in classrooms and support teachers in navigating these challenges. It is common that PD offered to science teachers was designed with assumed high disciplinary climates. We should ask, to what extent does the PD sessions target science teachers' needs and teaching context? Without alignment between PD and teachers' practice environment, some innovative PD might undermine science teachers' practice in low disciplinary climate classrooms, because teachers might remain hesitant or unprepared to implement practices espoused during PD sessions. More research that attends to the environmental factors that may interact with PD is warranted.

Conclusion

The study found that there was a statistically significant relationship between student science achievement and CLE and school-level PD; it also found that the quality and focus of CLE variables, such as inquiry practice and teachers' feedback, were statistically significantly related to student science achievement. Importantly, the findings also provided empirical evidence that some PD program might not benefit teachers and students as expected in schools with low level of CLE. Further studies are needed to examine dimensions of learning environment climate variables other than their quantity and to further explore the ways of promoting science teaching and learning in schools with low level of CLE.

Data Availability This study applied open access secondary dataset.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Code Availability N/A

Appendix 1. HLM Models

Fully Unconditional Model

Level-1 Model

$PV1SCIE_{ij} = \beta_{0j} + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

Partially Conditional Model

Control Factors Model

Level-1 Model

$PV1SCIE_{ij} = \beta_{0j} + \beta_{1j}*(Gender_{ij}) + \beta_{2j}*(ESCS_{ij}) + \beta_{3j}*(Self\text{-}Efficacy_{ij}) + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

$\beta_{1j} = \gamma_{10}$

$\beta_{2j} = \gamma_{20} + u_{2j}$

$\beta_{3j} = \gamma_{30} + u_{3j}$

Science Classroom Learning Environment Model

Level-1 Model

$PV1SCIE_{ij} = \beta_{0j} + \beta_{1j}*(Gender_{ij}) + \beta_{2j}*(ESCS_{ij}) + \beta_{3j}*(Self\text{-}Efficacy_{ij}) + \beta_{4j}*(Inquiry\text{-}based\ Science\ Teaching\ and\ Learning_{ij}) + \beta_{5j}*(Directed\ Instruction_{ij}) + \beta_{6j}*(Teacher\ Support_{ij}) + \beta_{7j}*(Perceived\ Feedback_{ij}) + \beta_{8j}*(Adaption\ of\ Instruction_{ij}) + \beta_{9j}*(Discilinary\ Climate_{ij}) + \beta_{10j}*(Self\text{-}Efficacy_{ij}) + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + u_{0j}$

$\beta_{1j} = \gamma_{10}$

$\beta_{2j} = \gamma_{20} + u_{2j}$

$\beta_{3j} = \gamma_{30}$

$\beta_{4j} = \gamma_{40} + u_{4j}$

$\beta_{5j} = \gamma_{50} + u_{5j}$

$\beta_{6j} = \gamma_{60}$

$\beta_{7j} = \gamma_{70}$

$\beta_{8j} = \gamma_{80}$

$\beta_{9j} = \gamma_{90} + u_{9j}$

$\beta_{10j} = \gamma_{100}$

Fully Conditional Models

School-Level Control Factors Model

Level-1 Model

$PV1SCIE_{ij} = \beta_{0j} + \beta_{1j}*(Gender_{ij}) + \beta_{2j}*(ESCS_{ij}) + \beta_{3j}*(Self\text{-}Efficacy_{ij}) + \beta_{4j}*(Inquiry\text{-}based\ Science\ Teaching\ and\ Learning_{ij}) + \beta_{5j}*(Directed\ Instruction_{ij}) + \beta_{6j}*(Teacher\ Support_{ij}) + \beta_{7j}*(Perceived\ Feedback_{ij}) + \beta_{8j}*(Adaption\ of\ Instruction_{ij}) + \beta_{9j}*(Disciplinary\ Climate_{ij}) + \beta_{10j}*(Self\text{-}Efficacy_{ij}) + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + \gamma_{1j}*(Class\ Size_{ij}) + \gamma_{2j}*(School\ Type_{ij}) + u_{0j}$

$\beta_{1j} = \gamma_{10}$

$\beta_{2j} = \gamma_{20} + u_{2j}$

$\beta_{3j} = \gamma_{30}$

$\beta_{4j} = \gamma_{40} + u_{4j}$

$\beta_{5j} = \gamma_{50} + u_{5j}$

$\beta_{6j} = \gamma_{60}$

$\beta_{7j} = \gamma_{70}$

$\beta_{8j} = \gamma_{80}$

$\beta_{9j} = \gamma_{90} + u_{9j}$

$\beta_{10j} = \gamma_{100}$

School-Level PD Model

Level-1 Model

$PV1SCIE_{ij} = \beta_{0j} + \beta_{1j}*(Gender_{ij}) + \beta_{2j}*(ESCS_{ij}) + \beta_{3j}*(Self\text{-}Efficacy_{ij}) + \beta_{4j}*(Inquiry\text{-}based\ Science\ Teaching\ and\ Learning_{ij}) + \beta_{5j}*(Directed\ Instruction_{ij}) + \beta_{6j}*(Teacher\ Support_{ij}) + \beta_{7j}*(Perceived\ Feedback_{ij}) + \beta_{8j}*(Adaption\ of\ Instruction_{ij}) + \beta_{9j}*(Disciplinary\ Climate_{ij}) + \beta_{10j}*(Self\text{-}Efficacy_{ij}) + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + \gamma_{1j}*(Class\ Size_{ij}) + \gamma_{2j}*(School\ Type_{ij}) + \gamma_{3j}*(Requirement\ of\ PD_{ij}) + \gamma_{4j}*(Broad\ Science_{ij}) + \gamma_{5j}*(School\ Science_{ij}) + \gamma_{6j}*(PD\ Activity_{ij}) + \gamma_{2j}*(PD\ Types_{ij}) + u_{0j}$

$\beta_{1j} = \gamma_{10}$

$\beta_{2j} = \gamma_{20} + u_{2j}$

$\beta_{3j} = \gamma_{30}$

$\beta_{4j} = \gamma_{40} + u_{4j}$

$\beta_{5j} = \gamma_{50} + u_{5j}$

$\beta_{6j} = \gamma_{60}$

$\beta_{7j} = \gamma_{70}$

$\beta_{8j} = \gamma_{80}$

$\beta_{9j} = \gamma_{90} + u_{9j}$

$\beta_{10j} = \gamma_{100}$

Cross-Level Interaction Model

Level-1 Model

$PV1SCIE_{ij} = \beta_{0j} + \beta_{1j}*(Gender_{ij}) + \beta_{2j}*(ESCS_{ij}) + \beta_{3j}*(Self\text{-}Efficacy_{ij}) + \beta_{4j}*(Inquiry\text{-}based\ Science\ Teaching\ and\ Learning_{ij}) + \beta_{5j}*(Directed\ Instruction_{ij}) + \beta_{6j}*(Teacher\ Support_{ij}) + \beta_{7j}*(Perceived\ Feedback_{ij}) + \beta_{8j}*(Adaption\ of\ Instruction_{ij}) + \beta_{9j}*(Disciplinary\ Climate_{ij}) + \beta_{10j}*(Self\text{-}Efficacy_{ij}) + r_{ij}$

Level-2 Model

$\beta_{0j} = \gamma_{00} + \gamma_{1j}*(Class\ Size_{ij}) + \gamma_{2j}*(School\ Type_{ij}) + \gamma_{3j}*(Requirement\ of\ PD_{ij}) + \gamma_{4j}*(Broad\ Science_{ij}) + \gamma_{5j}*(School\ Science_{ij}) + \gamma_{6j}*(PD\ Activity_{ij}) + \gamma_{2j}*(PD\ Types_{ij}) + u_{0j}$

$\beta_{1j} = \gamma_{10}$

$\beta_{2j} = \gamma_{20} + u_{2j}$

$\beta_{3j} = \gamma_{30}$

$\beta_{4j} = \gamma_{40} + \gamma_{41}*(Requirement\ of\ PD_{ij}) + \gamma_{42}*(PD\ Activity_{ij}) + u_{4j}$

$\beta_{5j} = \gamma_{50} + \gamma_{51}*(Requirement\ of\ PD_{ij}) + \gamma_{52}*(PD\ Activity_{ij}) + u_{5j}$

$\beta_{6j} = \gamma_{60}$

$\beta_{7j} = \gamma_{70}$

$\beta_{8j} = \gamma_{80}$

$\beta_{9j} = \gamma_{90} + \gamma_{91}*(Requirement\ of\ PD_{ij}) + \gamma_{92}*(PD\ Activity_{ij}) + u_{9j}$

$\beta_{10j} = \gamma_{100}$

Appendix 2

Items or Item Parameters for Independent Variables

Independent variables	Variable name	Items or item parameters for each derived variables
Science CLEs (student level)	Inquiry-based science teaching and learning	When learning <school science> topics at school, how often do the following activities occur? - Students are given opportunities to explain their ideas - Students spend time in the laboratory doing practical experiments - Students are required to argue about science questions - Students are asked to draw conclusions from an experiment they have conducted - The teacher explains how a <school science> idea can be applied to a number of different phenomena (e.g., the movement of objects, substances with similar properties) - Students are allowed to design their own experiments - There is a class debate about investigations - The teacher clearly explains the relevance of <broad science> concepts to our lives
	Directed instruction	How often do these things happen in your lessons for this <school science> course? - The teacher explains scientific ideas - A whole class discussion takes place with the teacher - The teacher discusses our questions - The teacher demonstrates an idea
	Teacher support	How often do these things happen in your <school science> lessons? - The teacher shows an interest in every student's learning - The teacher gives extra help when students need it - The teacher helps students with their learning - The teacher continues teaching until the students understand - The teacher gives students an opportunity to express opinions
	Perceived feedback	How often do these things happen in your lessons for this <school science> course? - The teacher tells me how I am performing in this course - The teacher gives me feedback on my strengths in this subject - The teacher tells me in which areas I can still improve - The teacher tells me how I can improve my performance - The teacher advises me on how to reach my learning goals
	Adaption of instruction	How often do these things happen in your lessons for this <school science> course? - The teacher adapts the lesson to my class's needs and knowledge - The teacher provides individual help when a student has difficulties understanding a topic or task - The teacher changes the structure of the lesson on a topic that most students find difficult to understand
	Disciplinary climate	How often do these things happen in your lessons? - Students do not listen to what the teacher says - There is noise and disorder - The teacher has to wait a long time for students to quiet down - Students cannot work well - Students do not start working for a long time after the lesson begins
	Instrumental motivation	How much do you agree with the statements below? - Making an effort in my subject(s) is worth it because this will help me in the work I want to do later on

(continued)

Independent variables	Variable name	Items or item parameters for each derived variables
		- What I learn in my subject(s) is important for me because I need this for what I want to do later on - Studying my subject(s) is worthwhile for me because what I learn will improve my career prospects - Many things I learn in my subject(s) will help me to get a job
Science teacher PDs (school level)	PD participation requirements	Are you required to take part in professional development activities?
	Proportion of broad science	During the last 12 months, what proportion of your professional development activities was dedicated to each of the following areas? <Broad science> and technology content matter
	Proportion of PD in school science	During the last 12 months, what proportion of your professional development activities was dedicated to each of the following areas? Teaching and learning <school science>: teaching methodology related to <school science>, instructional skills (e.g., use of experiments), student misconceptions
	Proportion of PD within 12 months	During the last 12 months, did you participate in any of the following activities?
	Different types of PD within 12 months	- Qualification program - Participation in a network of teachers formed specifically for the professional development of teachers - Individual or collaborative research on a topic of interest to you professionally - Mentoring and/or peer observation and coaching, as part of a formal school arrangement - Reading professional literature (e.g., journals, evidence-based papers, thesis papers) - Engaging in informal dialogue with your colleagues on how to improve your teaching

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