THE IMPACT OF TEACHERS' PROFESSIONAL DEVELOPMENT IN SCIENCE PEDAGOGY ON STUDENTS' ACHIEVEMENT: EVIDENCE FROM TIMSS 2019

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Abstract. *Teachers' professional development (PD) is considered to be a topic of interest in science education. This study examines the impact of professional development in science pedagogy (PD in PED) on students' achievement and how it influences teachers' instruction based on the Trends in International Mathematics and Science (TIMSS)2019. The sample comprised 2,968 fourth-grade students and their 145 teachers and 3,265 eighth-grade students and their 150 teachers in Hong Kong. Teachers' emphasis on science investigation (TESI) was included as a mediating factor. Multilevel mediation analyses revealed that PD in PED was significantly positively related to students' science achievement, while the link between PD in PED and students' science achievement was positively and completely mediated by TESI in the fourth grade. However, TESI had no mediating effect in the eighth grade, a finding that may be attributed to the characteristics of teacher PD programmes in different grades. The results also show that many teacher PD programmes are not of high quality and are intellectually superficial from the perspective of students' achievement gains. Implications for teacher PD practices are discussed as well.*

Keywords: professional development, science achievement, hierarchical linear model, TIMSS

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Introduction

Teachers are the implementors of educational policies. Hence, teacher professional development (PD) is undoubtedly the focus of academic research and the key to science education practice reform. There is no other area within science education that affects academics, practice, and students as comprehensively as the aforementioned development does. Considering the development's ultimate goal of teaching students to learn so they themselves develop excellently, the impact of such development is worthy of attention. There is a recognised need for teacher professional development that has a major impact on student outcomes (Andersson & Palm, 2017; Johnson et al., 2007a); however, research has shown that many professional development initiatives appear to be ineffective in supporting changes in teacher practices (Darling-Hammond et al., 2017). The idea that PD can foster improvements in teaching is widely accepted: In Hong Kong, PD is required by virtually every teaching contract, and teachers must participate in PD every year (Gore et al., 2017). Nevertheless, few studies have provided persuasive evidence of such activities' impact within actual school environments and on students' academic achievements, respectively. Moreover, there is a lack of proof as to whether different PD programmes produce a similar impact on teacher practices. This is also so with regards to schools which differ in level, namely, primary and secondary schools.

Meanwhile, a large body of research has shown that teachers' instructional approaches have important implications for student outcomes (Hubber et al., 2010; Ismail et al., 2018; Lin & Tsai, 2021). Improving teachers' pedagogy ability through PD in pedagogy (PD in PED) is the main approach. Examining the potential benefits of teachers' pedagogy can reveal specific recommendations that could be adopted in wide-ranging contexts. The current study examined data from the Trends in International Mathematics and Science Study 2019 (TIMSS 2019) to determine the unique influence that effective PD in science pedagogy has on student science achievement and the underlying mechanism of this relation in the fourth and eighth-grade contexts in Hong Kong.

Literature Review

Impact of Professional Development on Student Achievement

Although there is no literature on the relation between PD in PED and students' achievement, numerous studies have found that various pedagogies can change teachers' practices and students' learning (Adjapong & Emdin, 2015; Asamoah et al., 2020; Baker, 2013; Özdem et al., 2017), and some have discussed the features of different pedagogy in science teaching (Pugh & Girod, 2007; Schindel, 2016).

Further, a vast amount of contemporary research has tested the relation between teachers' PD and students' achievement, much of which has aimed to prove that teachers' PD can dramatically positively predict student achievement (Didion et al., 2020; Fischer et al., 2018; Piper et al., 2018; Taylor et al., 2017). The guidance function and impact of PD on teachers, and the effect of PD towards results of students, have all been analysed by several extensive explanatory trials of specific PD models (Jacob et al., 2017; Llosa et al., 2016; Roth et al., 2019). Meanwhile, the positive impacts of teachers' PD and, to some extent, its positive impacts on student outcomes can be found in the literature (Akiba & Liang, 2016; Fischer et al., 2020; Zakharov et al., 2020); however, some studies have failed to find any consistent association between teachers' PD and student achievement (Guskey & Yoon, 2009; Jacob et al., 2017). Antoniou and Kyriakides (2011) observed that a different approach to teacher professional development led to varying degrees of improvement in student achievement. Data from Germany in PISA 2003 showed the positive impact of teachers' PD programmes on students' interest, motivation, and outcomes in science and mathematics (Ostermeier et al., 2010).

Hundreds of experimental and quasi-experimental research studies, including both small and medium-sized, have studied PD interventions, whose results can enable educational scientists, policymakers, and regional leaders to understand the characteristics of effective PD. However, small studies can be difficult to interpret because they lack the ability to determine statistically significant effects (Gore et al., 2017). Most of the supporting empirical evidence was collected in research settings, rather than in normal school environments, and research on whether and how pedagogy PD programmes impact student achievement is especially rare.

Influence of PD Participation on Teachers' Instructional Practices

Desimone's research in 2002 is the largest and most influential related study, which demonstrated teachers' PD and its impacts on changing teaching practices in mathematics and sciences via a three-year longitudinal investigation (Desimone et al., 2002). Thereafter, Desimone's (2009) follow-up study found that the most direct results of teachers' participation in PD activities were improvements in their knowledge and skills and changes in their classroom instruction, which can indirectly lead to improvements in students' learning. Thus, one's experience as a teacher might abate PD's efficacy towards student accomplishment.

Korthagen (2016) identified that teachers' PD was effective at influencing their classroom behaviour. In the same vein, Bruce and Ross (2008) found that teachers implemented key strategies for effective mathematics teaching after peer coaching, while in their book *Effective Teacher Professional Development*, Darling-Hammond et al. (2017) demonstrated that structured professional learning that results in changes in teacher practices had a major impact in this field. A few experimental or quasi-experimental studies have also found science teachers to show notable performance advancement in relation to their PD (Al-Balushi & Al-Abdali, 2015; Buczynski & Hansen, 2010; Roth et al., 2011).

Impact of Science Investigation on Student Achievement

According to the National Science Education Standards (NRC, 1996), 'science investigation' forms part of what is called 'scientific inquiry'. Since the Next Generation Science Standards (NGSS) were promulgated in 2011, 'science practice' has also become a popular term in the field of science education. Over the years, the phrases 'science investigation', 'scientific inquiry', and 'scientific practices' have often been used interchangeably in the literature, although educational practitioners are most familiar with 'scientific inquiry'. However, though much of the extant literature has confirmed that scientific inquiry is an important factor in science learning, findings on the effects of scientific inquiry on student achievement have been inconsistent. Many empirical studies have observed that scientific inquiry has a positive impact on student achievement (Forbes et al., 2020; Jiang & McComas, 2015; Johnson

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et al., 2007a; Lati et al., 2012; Wen et al., 2020), although others have found negative effects (Areepattamannil, 2012; Cairns & Areepattamannil, 2019), and yet others have confirmed that the impact of scientific inquiry is extremely complex (Cairns, 2019; Teig et al., 2018).

Theoretical Framework

This study attempted to validate that teachers' PD in science pedagogy participation can increase students' science achievement. It also examines educational practice as a potential process factor of the relation between teacher's PD in science pedagogy participation and students' science achievements in the fourth and eighth grades. The theoretical framework in this study is consistent with those of Desimone et al. (2013), which is similar in scope and refined Desimone's (2009) framework structure. As shown in Figure 1, PD in science pedagogy has a direct influence on students' achievement and teachers' emphasis on science investigation, while PD in science pedagogy influences students' achievement through teachers' emphasis on science investigation, teachers' emphasis on science investigation acted as a mediator. Among them, PD in science pedagogy can increase teachers' knowledge and skills, teachers' emphasis on science investigation can change teachers' practice, and students' achievement is the result of improving students' learning.

Figure 1
Modes of PD in Science Pedagogy on Teachers and Students [adapted from Desimone (2009)]
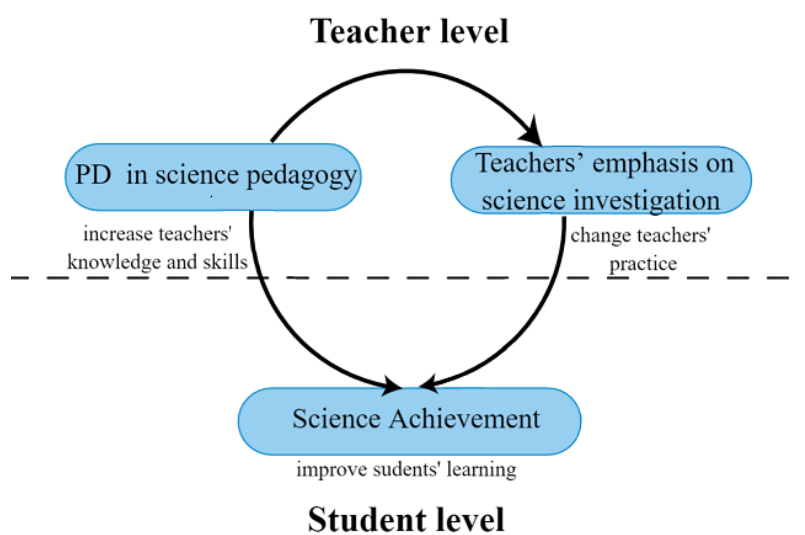
Research Hypotheses

The research hypotheses were as follows:
    H1: Teachers' PD in science pedagogy participation has a positive impact on fourth-grade and eighth-grade students' science achievement.
    H2: Teachers' emphasis on science investigation is a mediating factor between teachers' PD in science pedagogy participation and students' science achievement in the fourth and eighth grades, and it positively impacts on students' science achievement.

Research Methodology

General Background

The hierarchical linear model was adopted as an analytic strategy. This study used Hong Kong 278 schools' fourth and eighth grade data which was collected from teacher and students' questionnaires and in TIMSS 2019. TIMSS is an international assessment of student achievement in mathematics and science at fourth and eighth grades, conducted every four years since 1995. When the TIMSS2019 data collection began in the first half of 2019, it was largely unaffected by the COVID-19 pandemic.

Participants

The sampled students comprised 3,026 fourth-graders and 3,377 eighth-graders. There were 58 missing data for the fourth-grade group; therefore, we ultimately analysed 2,968 data valid items. The sample comprised 53.5% boys and 46.5% girls from 142 schools. This sample also included 145 fourth-grade science teachers, including teachers who taught both maths and science. 59.2% were female, and 40.8% were male, and there were three missing data items. There was a total of 3,377 participants in the eighth grade; with 112 missing data, the valid data totalled 3,265 items. The sample included 54.2% boys and 45.8% girls from 136 schools. The sample also included 150 science teachers. Eight data items were missing; 41.5 % were female, and 58.5% were male. As the sponsor, IEA (International Association for the Evaluation of Educational Achievement) ensure that all involved are well informed about the correct methods and protocols, participate in this study that was obtained at the beginning of data collection in accordance with educational research ethics (IEA, 2022).

Instrument and Procedures

Professional Development in Science Pedagogy/Instruction

The professional development in science pedagogy/instruction by both fourth and eighth-grade teachers was measured with the question: 'In the past two years, have you participated in professional development in any of the following? Science pedagogy/instruction' (Yes = 1; No = 0).

Science Achievement

According to TIMSS 2019 International Database, five estimates, also named 'plausible values', were separately made on each student's score on each achievement scale. Innate uncertainty was outlined in the variability between the five. Under the circumstance of the said database, the plausible values made the A-list procurable metric in measuring the students' achievement on the specific scale, thus ought to be set as the gauge for the outcome when researching student achievement; thus, the fourth and eighth graders' science achievement data were used in the present analysis.

Teachers' Emphasis on Science Investigation

The Teachers' Emphasis on Science Investigation scale was created to measure teachers' instructional practices and was based on teachers' responses to the eight items listed below, which included, 'When teaching science to the students in this class, how often do you ask them to do the following? (1) Fourth grade: Observe natural phenomena such as the weather or a plant growing and describe what they see / Eighth-grade: Observe natural phenomena and describe what they see; (2)Watch me demonstrate an experiment or investigation ;(3) Design or plan experiments or investigations ;(4) Conduct experiments or investigations ;(5) Present data from experiments or investigations ;(6) Interpret data from experiments or investigations ;(7) Use evidence from experiments or investigations to support conclusions and (8) Do fieldwork outside the class'. Teachers responded on a 4-point scale (*4*= Every or almost every lesson;*3*= About half the lessons;*2*= Some lessons;*1*=Never).

Covariates

Student-level covariates included gender (0 = boy,1 = girl), and 'home resources for learning' in the fourth grade or 'home educational resources' in the eighth grade (there were slight differences in the home resources scale in two grades context questionnaires). 'Home resources for learning' items (fourth grade) included (1) Number of books in the home; (2) Number of home study supports—which featured on the students' context questionnaire—and (3) Number of children's books in the home; (4) Highest level of education of either parent; (5) Highest level of occupation of either parent, which featured on the home context questionnaire.

In the eighth-grade questionnaire, Q3 ('Number of children's books in the home') and Q5 ('Highest level of occupation of either parent') were deleted, and the scale was named 'Home educational resources' (as opposed to 'Home resources for learning' in the fourth-grade questionnaire), although both scales represented the families' socioeconomic status. Previous studies have shown the above factors are significantly related to students' achievements; for example, using data from TIMSS 2011, Reilly et al. (2019) found that in non-OECD nations, girls scored higher than boys in mathematics and science achievement. In the US, Quinn and Cooc (2015) revealed that girls outperformed boys in Grade 3, although this gap may narrow slightly by the eighth grade. Furthermore, since the Coleman Report (1988), extensive research has been conducted on the relation between socioeconomic status and academic achievement (Blums et al., 2017; Sarsour et al., 2011), and the results of PISA 2015 indicated that the strength of the relationship between socio-economic status and scientific achievements was significantly connected to the country's income level (Liu et al., 2020). However, there is inconsistency among existing research results, coupled with little understanding of the relationship between students' socio-economic status and scientific achievements in Hong Kong. Thus, in the present study, the variables mentioned above are considered as covariates.

Teacher-level covariates were reported by each teacher and included the items 'gender' (0 = male, 1 = female) and 'What is the highest level of formal education you have completed?' A higher level of knowledge in science and mathematics was discovered by Wayne and Youngs (2003) to have a positive correlation with student achievements, while Chudgar and Sankar (2008) demonstrated that having a female teacher is advantageous for student's language learning. Using data from a five-year panel, Winters et al. (2013) also estimated a statistically significant relation between teacher gender and student achievement in middle and high school. Moreover, a large body of literature has demonstrated that teacher's gender affects children's science achievement scores, although consistent conclusions have not been reached (Beilock et al., 2010; Lee et al., 2019; Muralidharan & Sheth, 2016; Tatar et al., 2016).

To control for the impact of other teacher PD programmes, whether the teacher had ever attended additional programmes in the seven areas in the previous two years was included in the form of the following covariates: (1) science content, (2) science curriculum, (3) integrating technology into science instruction, (4) improving students' critical thinking or inquiry skills, (5) science assessment, (6) addressing individual students' needs, (7) integrating science with other subjects (1= yes, 0 = no). 'Integrating science with other subjects' was deleted from the eighth-grade questionnaire.

Statistical Analyses

SPSS 23 and hierarchical linear modelling (HLM 6.08, Scientific Software International, Skokie, Il) were used to take the nested data structure (students as the individual level units on level 1, nested within teachers as the group-level unit on level 2) into account because HLM was able to appropriately address the hierarchically nested design of the study (Hofmann, 1997).

At first, the intra-class correlation coefficient (ICC) was calculated by researchers for the obtainment of unconditional models' outcome and mediator variables (Hofmann, 1997). The fact that group-level characteristics can justify a responding variable's variance is shown by ICC (Woltman et al., 2012). Besides, a notable variance of a responding variable among groups is implicitly suggested given ICC value's surpassing of the 0.059 standard. Consequently, a hierarchical linear analysis is necessitated (Wen & Chiou, 2009). In this study, science achievement was entered into the HLM analysis as a dependent variable, with no predictors in the model; the results indicated significant variance of science achievement among the teachers. Therefore, in the analysis, teacher-level independent variables were entered into level 2 and student-level independent variables were entered into level 1 analysis.

The continuous variables, including the dependent variables, were standardised using Z scores across all of

the teachers in the study, in a method similar to the grand-mean centre method suggested by statistical methodologists (Zhang et al., 2016). Dummy variables, such as gender or whether teachers had ever attended PD programmes, were uncentered.

Using the fourth-grade statistical analyses as an example, the independent variable (PD in PED) must be related to the dependent variables (science achievement) after controlling for the student level (gender, home resources for learning) and teacher level (teacher gender, formal education level, attendance of the other seven PD programmes) covariates: coefficient c in Eq 1.

Level 1: Science Achievement$_{ij}$=β_{0j}+ β_{1j}(SGENDER$_{ij}$) + β_{2j}(HRL$_{ij}$) +r$_{ij}$

Level2: β_{0j}= γ_{00} +c/γ_{01}(PED$_j$) + γ_{02}(CON$_j$) + γ_{03}(CUR$_i$) + γ_{04}(TEC$_j$) + γ_{05}(CRI$_j$) + γ_{06}(ASS$_j$) + γ_{07}(NEED$_j$) + γ_{08}(INTSUB$_j$) + γ_{09}(TGENDER$_j$) + γ_{010}(TEDU$_j$) +u$_{0j}$

β_{1j}= γ_{10}+u$_{1j}$

β_{2j}= γ_{20}+u$_{2j}$

Notes: SGENDER: *gender of student*; HRL: *home resources for learning*; PED: *PD in Science pedagogy/instruction*; CON: *PD in science content*; CUR: *PD in science curriculum;* TEC: *PD in integrating technology into science instruction*; CRI: *PD in improving students' critical thinking or inquiry skills*; ASS: *PD in science assessment*; NEED: *PD in addressing individual students' needs*; INTSUB: *PD in integrating science with other subjects*; TGENDER: *gender of teacher*; TEDU: *the highest level of formal education the teacher had completed*.

Secondly, the independent variable (PD in PED) must correlate with the mediator (TESI) after controlling for covariates: coefficient a in Eq 2.

TESI=β_0+a/β_1(PED$_j$)+β_2(CON$_j$)+β_3(CUR$_j$)+β_4(TEC$_j$)+β_5(CRI$_j$)+β_6(ASS$_j$)+β_7(NEED$_j$)+β_8(INTSUB$_j$)+β_9(TGENDER$_j$)+β_{10}(TEDU$_j$)+ u$_t$

Thirdly, a connection must be established between the responding variable (achievement in science) and the mediator variable (TESI) when the predictor (PD in PED) is under control: coefficient b in Eq 3. Coefficient c' represented the relationship betwixt accomplishment in science and PD in PED.

Level 1: Science Achievement$_{ij}$=β_{0j}+ β+ β_{1j}(SGENDER$_{ij}$) + β) + β_{2j}(HRL$_{ij}$) +) +r$_{ij}$

Level 2: β_{0j}= γ_{00} +c'/γ_{01}(PED$_j$) + γ_{02}(CON$_j$) + γ_{03}(CUR$_i$) + γ_{04}(TEC$_j$) + γ_{05}(CRI$_j$) + γ_{06}(ASS$_j$) + γ_{07}(NEED$_j$) + γ_{08}(INTSUB$_j$) + γ_{09}(TGENDER$_j$) + γ_{010}(TEDU$_j$) + b/ γ_{011}(TESI$_j$) +u$_{0j}$

β_{1j}= γ_{10}+u$_{1j}$

β_{2j}= γ_{20}+u$_{2j}$

The incidental impact of PD in PED on students' accomplishments in science is caused when path a is multiplied by path b. The reduction in path from PD in PED to students' achievement in science still allows for the happening of partial mediation provided said path was nonetheless notable with the mediator TESI in the model. However, when said path was insignificant as the mediator's existence, complete mediation took place.

Research Results

Descriptive and Correlation Results

Table 1

Descriptive and Correlational Statistics for Student and Teacher Variables in the Fourth Grade

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pearson Correlation														
1. Student gender														
2. Home resources for learning	-.024													
3. Teacher gender	.067***	-.012												
4. Formal education	.022	-.008	-.029											
5. Science content	.036	.009	.054**	-.082***										

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	1	2	3	4	5	6	7	8	9	10	11	12	13	14
6. Science pedagogy/instruction	.033	.088***	-.059**	-.089***	.590***									
7. Science curriculum	.019	.077***	.032	.017	.667***	.584***								
8. Integrating technology	-.020	.020	.020	-.093***	.603***	.485***	.484***							
9. Student critical thinking	-.026	-.007	.044*	-.084***	.435***	.450***	.423***	.504***						
10. Science assessment	.043*	-.042*	-.017	-.056**	.446***	.466***	.412***	.428***	.437***					
11. Student needs	-.038*	-.072***	-.004	-.051**	.123***	.179***	.121***	.091***	.381***	.357***				
12. Integrating science subjects	-.018	-.010	.074***	-.092***	.328***	.300***	.265***	.482***	.361***	.359***	.240***			
13. TESI	-.011	.060**	-.076***	-.116***	.059**	.057**	-.004	-.010	.048**	-.003	.074***	.051**		
14. Science achievement	-.007	.397***	.026	-.030	.041*	.075***	.071***	.022	.017	-.068***	-.059**	-.008	.102***	
Descriptive statistics														
M		10.48		5.19									8.68	532.53
SD		1.92		0.5									2.08	70.20
MIN		3.82		4									6.59	245.65
MAX		14.88		6									16.14	744.67

Note. *p<.05; **p<.01; ***p<.001.

Table 2
Descriptive and Correlational Statistics for Student and Teacher Variables in the Eighth Grade

	1	2	3	4	5	6	7	8	9	10	11	12	13
Pearson Correlation													
1. Student gender													
2. Home educational resources	.076***												
3. Teacher gender	.017	-.002											
4. Formal education	.062***	.061***	-.002										
5. Science content	-.065***	-.020	-.050**	.210***									
6. Science pedagogy/instruction	.015	.023	.072***	-.045*	.277***								
7. Science curriculum	.002	-.015	.024	.086***	.500***	.350***							
8. Integrating technology	.052**	.081***	.013	.216***	.371***	.364***	.545***						
9. Student critical thinking	.013	.081***	.148***	.050**	.174***	.360***	.286***	.351***					
10. Science assessment	-.036*	.127***	.066***	-.077***	.277***	.383***	.391***	.341***	.562***				
11. Student needs	-.072***	.053**	.088***	.170***	.132***	.091***	.213***	.271***	.232***	.223***			
12. TESI	-.019	.047**	-.035*	.065***	.203***	.188***	.105***	.095***	.179***	.070***	.053**		
13. Science achievement	.007	.258***	-.012	.074***	-.024	.050**	.034	.060**	.070***	.085***	.073***	.086***	
Descriptive statistics													
M		10.28		5.47								9.41	498.79
SD		1.55		0.554								1.78	93.30
MIN		4.55		4								6.51	178.19
MAX		13.52		7								16.03	773.86

Note. *p < .05; **p < .01; ***p < .001.

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Multilevel Mediation Analyses of The Fourth Grade

As Table 3 shows (Step 1), there was a significant main impact of PD in PED on students' science achievement after controlling for all covariates (β=0.316, t=2.058, p < .05), such that teachers' attendance of PD in PED in the previous two years was related to their students' higher science scores. After establishing the main impact of PD in PED on students' science achievement, it was also shown that home resources for learning had a large and statistically significant positive impact (β=0.205, t=7.962, p < .001) on science achievement. However, unexpectedly, PD in science assessment had a negative effect (β=-0.341, t=-2.247, p < .05).

The next step was to establish associations between PD in PED and the mediator TESI. Table 3 (Step 2) shows that teachers' attendance of science pedagogy PD in the previous two years was related to higher ratings of TESI among them (β=0.158, t=3.063, p < .01). All the other programmes also showed significant impacts except for PD in integrating science subjects. Notably, several programmes had a negative impact on TESI––—PD in science curriculum (β=-0.271, t=-4.925, p < .001), PD in integrating technology (β=-0.326, t=-5.641, p < .001), PD in science assessment (β=-0.203, t=-3.943, p < .001)—although some had a positive impact: PD in science content (β=0.292, t=5.067, p < .001), PD in student critical thinking (β=0.269, t=5.203, p < .001), and PD in student needs (β=0.149, t=3.485, p < .01). Furthermore, in this step, teachers' gender and educational levels were shown to have a significant negative impact on TESI; in other words, male teachers with lower educational levels placed more emphasis on science investigation.

Step 3 established the impact of the mediator on the dependent variable when controlling for PD in PED and other covariates. Table 3 (final column) shows that higher ratings of TESI were associated with higher science scores (β=0.192, t=3.406, p =.001). Specifically, science scores increased by 0.192 unit for every unit increase in TESI. As such, the association between PD in PED and achievement was assumed to be either nonsignificant or of lesser magnitude when taking the mediators into account. When comparing parameter estimates of the association between PD in PED and achievement, the final estimate was of lesser magnitude than the first (β=0.289 vs. 0.316; t=1.963, p>.05); it had declined by 0.03 and the independent variable no longer had a significant influence on the dependent variable, demonstrating complete mediation. To further test the indirect impact of PD in PED and achievement (path ab; see Figure 2), we followed Krull and MacKinnon (1999). The specific pathway from PD in PED to science achievement through TESI was significant (Sobel's z=2.298, p = .02; see Figure 2).
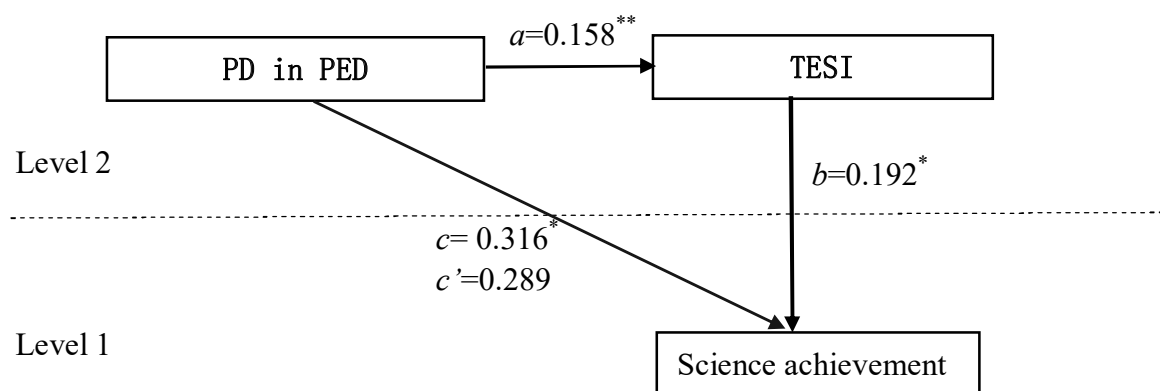
Figure 2
Mediation Model for the Fourth Grade

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Table 3

Mediation Analyses: Association between PD in PED and Students' Science Achievement through TESI in the Fourth Grade

	STEP 1: Dependent Science achievement			STEP 2: Dependent TESI (AdjR^2=0.082, F=25.753)			STEP 3: Dependent Science achievement		
	β	SE	t	β	SE	t	β	SE	t
Intercept	-0.170	0.644	-0.265	1.561***	0.208	7.521	-0.476	0.604	-0.789
Level 1 covariates									
Student gender	-0.053	0.037	-1.421				-0.05	0.037	-1.376
Home resources for learning	0.205***	0.026	7.962				0.206***	0.026	7.999
Level 2 covariates									
Teacher gender	0.073	0.112	0.651	-0.213***	0.040	-5.356	0.110	0.103	1.067
Formal education	0.015	0.113	0.130	-0.282***	0.039	-7.303	0.070	0.109	0.642
Science content	-0.089	0.154	-0.578	0.292***	0.058	5.067	-0.150	0.165	-0.908
Science curriculum	0.102	0.143	0.709	-0.271***	0.055	-4.925	0.138	0.146	0.947
Integrating technology	0.038	0.149	0.254	-0.326***	0.058	-5.641	0.111	0.145	0.761
Student critical thinking	0.101	0.122	0.824	0.269***	0.052	5.203	0.058	0.117	0.500
Science assessment	-0.341*	0.152	-2.247	-0.203***	0.052	-3.943	-0.294	0.154	-1.906
Student needs	-0.062	0.105	-0.587	0.149**	0.043	3.485	-0.091	0.109	-0.833
Integrating science subjects	-0.072	0.116	-0.622	0.011	0.047	0.238	-0.082	0.110	-0.745
Level 2 independent									
PD in PED	0.316*	0.154	2.058	0.158**	0.051	3.063	0.289	0.147	1.963
Level 2 mediator									
TESI							0.192**	0.056	3.406
Random Effects									
Deviance -2x log	6617.394						6608.849		
Difference △-2x log	73.975						8.545		

Note. ICC1was calculated with the intercept-only model (Null Model: Science achievement=$\beta_{0j+}u_{0j}$); ICC1= $\tau^2/(\tau^2+\sigma^2)$. This gives the percentage of variance that is attributable to differences between teachers (τ^2=variance between teachers; σ^2=variance between students). Null Model: ICC1=32.34%, σ^2= 0.684, τ^2= 0.327, Deviance -2x log=6691.369; Intercept: $\beta0j$=-0.016, *SE*=0.058, *P*=.781. *$p < .05$; **$p < .01$; ***$p < .001$.

Multilevel Mediation Analyses of The Eighth Grade

As evident in Table 4 (Step 1), students' gender (β=-0.128, *t*=-4.262, *p* < .001) and home educational resources (β=0.074, *t*=4.772, *p* < .001) and teachers' educational levels (β=0.326, *t*=2.487, *p* < .05) and PD in science content (β = -0.345, *t*=-2.371, *p* < .05) had significant direct impacts on science achievement: male students with more home educational resources taught by teachers with higher levels of formal education who had not attended PD in science content achieved higher science scores. However, PD in PED was not related to students' science achievement (β=0.135, *t*=0.765, *p* > .05).

According to Table 4 (Step 2), PD in PED showed a significant positive impact on TESI (β =0.640, *t*=7.023, *p* < .001). In addition, several PD programmes had a large negative impact on TESI, including PD in integrating technology (β =-0.282, *t*=-2.977, *p* < .01), PD in science assessment (β =-0.332, *t*=-3.475, *p* < .01), and PD in student needs (β =-0.331, *t*=-4.056, *p* < .001). Conversely, PD in science content (β =0.579, *t*=6.153, *p* < .001) and PD in student critical thinking (β =0.517, *t*=5.142, *p* < .001) were both significantly positively associated with TESI.

As shown in Table 4 (Step 3), PD in PED (β =0.086, *t*=0.501, *p* > .05) was unrelated to students' science achievement, while TESI (β=0.137, *t*=2.252, *p* < .05) was positively related to such achievement, meaning that TESI was not a significant mediator between PD in PED and students' science achievement. Though the mediating impact of TESI

was not significant, the direct impact of TESI on students' science achievement was still investigated. A detailed model is presented in Figure 3.

Figure 3
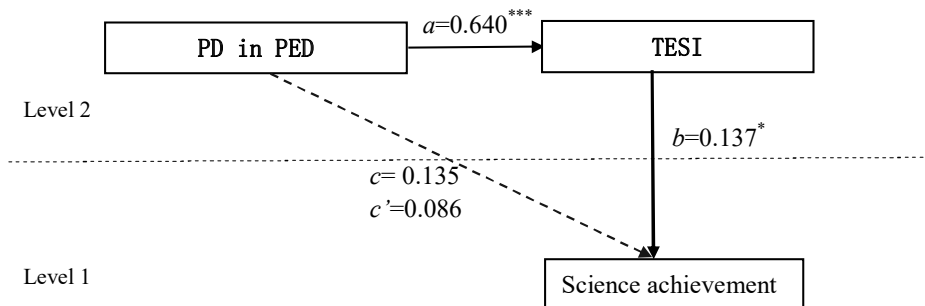*Mediation Model for the Eighth Grade*

Table 4
Mediation Analyses: Association between PD in PED and Students' Science Achievement through TESI in the Eighth Grade

	STEP 1: Dependent Science achievement			STEP 2: Dependent TESI (AdjR²=0.057, F=16.671)			STEP 3: Dependent Science achievement		
	β	SE	t	β	SE	t	β	SE	t
Intercept	-1.751*	0.729	-2.401	8.820***	0.372	23.726	-1.695*	0.727	-2.332
Level 1 covariates									
Student gender	-0.128***	0.030	-4.262				-0.128***	0.030	-4.264
Home educational resources	0.074***	0.016	4.772				0.074***	0.016	4.767
Level 2 covariates									
Teacher gender	0.120	0.132	0.906	-0.084	0.078	-1.077	0.126	0.130	0.966
Formal education	0.326*	0.131	2.487	0.008	0.067	0.117	0.324*	0.129	2.503
Science content	-0.345*	0.145	-2.371	0.579***	0.094	6.153	-0.402**	0.145	-2.768
Science curriculum	-0.041	0.196	-0.211	-0.133	0.099	-1.340	-0.026	0.193	-0.136
Integrating technology	0.017	0.191	0.087	-0.282**	0.095	-2.977	0.039	0.186	0.209
Student critical thinking	0.083	0.174	0.478	0.517***	0.101	5.142	0.044	0.172	0.258
Science assessment	0.215	0.167	1.288	-0.332**	0.096	-3.475	0.238	0.163	1.457
Student needs	0.086	0.155	0.556	-0.331***	0.082	-4.056	0.113	0.147	0.771
Level 2 independent									
PD in PED	0.135	0.176	0.765	0.640***	0.091	7.023	0.086	0.172	0.501
Level 2 mediator									
TESI							0.137*	0.061	2.252
Random Effects									
Deviance -2x log	6755.605						6753.152		
Difference △-2x log	45.572						2.453		

Note. ICC1 was calculated with the intercept-only model (Null Model: Science achievement=$\beta_{0j+}u_{0j}$); ICC1= $\tau^2/(\tau^2+\sigma^2)$. This gives the percentage of variance that is attributable to differences between teachers (τ^2=variance between teachers; σ^2=variance between students). Null Model: ICC1=59.79%, σ^2= 0.429, τ^2= 0.638, Deviance -2x log=6801.177 ; Intercept: β0j=-0.037, *SE*=0.079, *P*=.636. *$p < .05$; **$p < .01$; ***$p < .001$.

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Discussion

Association between PD in PED and Students' Science Achievement

With reference to previous studies, the researchers controlled for gender and home resources for learning at the individual student level (Sirin, 2005; Xuan et al., 2019) and gender and formal education at the teacher level (Toropova et al., 2019; Wayne & Youngs, 2003). The analysis of the data from the fourth grade revealed that students achieved higher science scores when the teacher had attended PD in PED in the previous two years. This was in stark contrast to the other types of PD programmes, which did not have any significant impact on students' science performance; in fact, the science assessment PD indicated significant negative effects. None of the teachers' PD activities were effective, and the science content PD programme indicated negative significant effects on eighth-grade students' performance.

The results provided evidence that many teacher PD programmes are not of high quality and are intellectually superficial from the perspective of students' achievement gains. No comparison of differences across grades in connection to TIMSS science achievement measures has been conducted to date. The results from the fourth-grade data are consistent with those reported by Buczynski and Hansen (2010) and Taylor et al. (2017), which observed that students in the middle and upper grades of primary schools can improve their science achievement when their teacher receives science pedagogical instruction, and PD can influence teachers' classroom practices. However, the observed association between PD in PED and science achievement in the eighth grade contrasted Johnson et al.'s (2007b) study, which revealed a positive impact of PD programmes on students' science achievement in the sixth to eighth grades. This contrast is likely related to the difference in developmental stages between fourth and eighth graders leading to changes in classroom characteristics; for example, fourth graders are more energetic, excitable, boisterous, and easily distracted by one another, meaning teachers must expend more energy on managing classroom discipline, whereas eighth-grade classrooms tend to be quieter. Therefore, fourth-grade teachers must use teaching methods to control the classroom and ensure the quality of teaching.

Furthermore, the results revealed that teachers' gender and formal education levels did not have positive impacts on student achievement in the fourth grade; however, their formal education levels had positive significant impacts on student achievement in the eighth grade: the higher the teacher's educational attainment, the higher their students' scores. One reason for this result is that compared with the fourth grade, the eighth-grade science curriculum content was slightly more difficult, thus requiring teachers to have a higher education level. Combined with the finding that only the PD in science content significantly affected student achievement in the eighth grade, this may be another indication that the reason teacher PD in PED does not have a significant impact on student achievement in higher grades is that teachers need other training to improve their teaching skills, such as PD in science content. The findings indicated that teachers' attendance of different PD programmes in different grades predicted students' science performance to varying degrees. This means that teachers of different grade require different kinds of PD programmes to allow students to profit from them, for instance, PD in PED is the most appropriate programme to improve student's achievement in the fourth grade.

Teachers were more willing to choose or accept the PD programmes provided by their school and the Education Bureau because teachers are often passively focused on their own PD. Appropriate PD training content should be selected based on an understanding of teachers' current needs, situation, and characteristics and the difficulties of students and teachers at different grade levels. Long-term PD plans should be developed to meet the diverse needs of teacher-learners, thus facilitating their more targeted participation in training and thereby improving the quality of training and promoting students' development.

The Mediation of TESI between PD in PED and Students' Science Achievement

These results suggest that PD in PED led to teachers' increased emphasis on science investigation and TESI could significantly impact students' science achievement in both grades, which supports the analyses of

Jiang and McComas (2015) and Forbes et al. (2020), although differs from the findings presented by Areepattamannil (2012) and Cairns and Areepattamannil (2019).

Furthermore, only a few PD programmes had a significant impact on students' science scores in the two grades, although almost all the programmes had a significant impact on TESI (for some, this impact was positive; for others, it was negative). This could imply that the PD programmes directly affected the teachers' practice (Bernard & Dudek,2020), thereafter indirectly affecting the students' achievements. As a result, instead of being confined in the experimental and quasi-experimental studies, the researchers consider it most necessary to combine the theory, Desimone's (2009) conceptual framework for teacher PD in real-world scenarios.

Consistent with previous studies (Buczynski & Hansen, 2010; Greenleaf et al., 2011), the results suggested that changes in teaching occur if teachers undertake appropriate professional development. What was disclosed by Desimone (2009) and Wayne et al. (2008) in their exploring of the mechanism of PD was substantiated by this study, namely, having experienced effective professional development, including aspects of knowledge, skills, attitudes, and beliefs change, teachers can utilize given instruction in the advancement of their own tutelage and pedagogical means, eventually, students' learning can thus be facilitated under such advancement.

Based on the above findings, policymakers and school authorities should pay more attention to providing PD programmes that teachers really need and make sense for teacher practice and focus on how teachers use the knowledge, content, or pedagogy to change student learning in the future. Hong Kong's education authorities should promote efficient, practical, and evidence-based teacher PD programmes; develop teacher PD programmes that are oriented to the actual needs of teachers; and instil more practical value in the courses. Based on the findings of previous research, a consortium of universities and primary and secondary schools should be established that allows teachers to participate in PD programmes with a coach or a highly knowledgeable teacher, which would result in a larger effect on improving teacher practice skills (Buczynski & Hansen, 2010; Jacob et al., 2017; Kapanadze et al.,2015). The goal of teacher PD must be changed from 'providing opportunities' to 'providing high-quality programmes'.

Beyond educational authorities, school-based or workshop-based PD programmes should also be encouraged. Since teacher's work is practical, dynamically changing, and varies according to the individual, what teachers need most is not to be centrally 'managed' according to uniform standards but to be encouraged, supported, and assisted according to the specific situation of the school and class. School-based learning plays a unique role in teachers' professional growth because it provides optional and customised training for teachers. With the vigorous development of online training, the personalised development of teachers has now become possible. Education authorities should enrich online resources for teachers to give them the opportunity to obtain personalised professional development resources.

With respect to research design, the present review introduces new questions about PD in PED and the role of TESI in students' science achievement. As in any secondary data analysis, some limitations should be noted when interpreting the findings. First, the results were based on self-reported questionnaire data, which potentially included social desirability bias. Second, the training components of PD are often combined organically rather than separately. The enhancement of teachers through PD involves a combination of the impacts produced by all aspects; therefore, in this study, it was difficult to separate the impacts of PD in PED from those of other training components. Third, only dichotomous variables (yes or no) were included in the PD programmes scale. Adding intensity, duration, or other dimensions that can represent the efficiency of PD could have yielded more robust findings. Furthermore, among the many science pedagogies that have been found to be effective in science teaching (Slavin et al., 2014), such as inquiry-based pedagogy, problem-based learning, project-based learning, STEM, and so on, it is uncertain which most affects teacher practice and student achievement. Teachers' PD takes many forms; however, the data did not show whether the PD programmes teachers attended were large-scale programmes or peer coaching or whether they were run by full-time trained associates or small group facilitators who were hired specifically. Under ideal conditions, teachers should be followed up for at least one full year after PD is completed in order to find out to what extent they can maintain new practice after PD support disappears (Kennedy, 2016). Unfortunately, TIMSS does not collect information on this scale; therefore, the researchers did not have enough statistical power to investigate the impact of the above factors, which should be further explored in future research.

Fourth, according to previous research (Mellom et al., 2018), attached significant importance to the connection of PD and scholarly accomplishments, within the setting of Hong Kong, the inspiration and attitudes of teachers towards PD is worth deeper research. Finally, few longitudinal studies were available that have evaluated changes in the impact of PD in PED or other programmes on academic achievement over time. This study also did not provide concrete benchmarks for how to change the PD currently offered in Hong Kong. Future research on how to develop high-quality PD training, incorporate new ideas into ongoing practices, and the selection of appropriate PD programmes at different stages could be combined.

Conclusions and Implications

Basing on Desimone's conceptual framework of teachers' PD, the research revealed direct and indirect links between PD in PED and science achievement in the fourth grade, though the direct impact was weak to some extent. Consequently, the results confirmed both the hypotheses in the fourth-grade context; however, these assumptions were not confirmed in the eighth grade. It was regrettable that the study also found that not all PD programs improved students' achievement, and some even had a negative impact, it complements the existing conclusions in the field. Hence, numerous unanswered questions remain with regards to the finest method to perfect PD and its potential for teacher practice and student achievement. Given this situation, the researchers must contemplate the most ideal method in the provision of guidance and encouragement to promote this trend, such as improve the quality of PD programs and give teachers more independent rights to choose targeted courses and so on.

The results also pointed to a mechanism in which PD in PED led to teachers' increased emphasis on science investigation in both grades. In the fourth grade, TESI completely mediated the relation between PD in PED and science achievement after controlling for the influences of teachers' gender, level of formal education, and other programmes they had attended in the previous two years. In the eighth grade, though PD in PED was unrelated to students' science achievement, it did significantly impact teachers' emphasis on science investigation. Further, the results also showed that higher degrees of TESI had a significant positive impact on students' science performance in both grades. Although PD plays a relatively limited role in directly improving student performance, it can promote teachers' practices largely. The importance of teacher practice has been strongly verified again in this study and the reasons why the two grades have different results and how teachers' practice in the classroom can be enhanced were discussed.

The current study demonstrated the impact of PD in PED on students' science achievement and simultaneously examining the mediating impact of TESI in Hong Kong, proved the theoretical model, extended the existing research which can contribute to developing both theory and practice. The findings indicated that PD study should focus on how different programmes impact teachers' practices and students' achievements and how to provide appropriate PD programmes in the future, also led the researchers to think whether the effectiveness of PD programs should be evaluated in terms of changing classrooms and improving students. Last decades have witnessed the advance of new technology and the relentless propel on the consolidation of the foundation for research on PD programmes in view of its plan, execution, and assessment, the scale of which may probably continue to be broadened drastically in the following years.

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Declaration of Interest

Authors declare no competing interest.

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