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Science teachers' collaborative innovative activities: the role of professional development and professional experience

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Despite the significant research interest in teachers' innovative activities, the role of work experience and professional development (PD) as predictors of science teachers' innovative work behaviour has rarely been studied. By using the TIMSS 2015 data of three countries with different levels of student achievements in science (Japan, Lithuania and South Africa), this article focuses on revealing how PD content, duration and teaching experience predict science teachers' two collaborative innovative activities: working together to try out new ideas and sharing new ideas. According to Rogers' diffusion theory, these two activities correspond to the fourth and fifth stages of innovation: implementation and sharing. The results of an ordinal regression analysis revealed that PD duration could not predict the collaborative innovative activity of science teachers and that teaching experience was a significant predictor of collaborative innovative activity only among Japanese teachers. The study showed that in Lithuanian and South African samples, PD focusing on pedagogical content knowledge, such as science curriculum, students' critical thinking and enquiry skills and addressing individual students' needs, positively predicted teachers' innovative activities. The study invites future research and discussion about the role of PD duration in the collaborative innovative activity of science teachers.

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Introduction

There is an increasing need for scientific knowledge in the future, but studies in many countries have indicated that it is difficult to engage students in science learning when traditional teaching methods are applied (Kennedy & Odell, 2014; Osborne & Dillon, 2008). Recently, innovations in science education have attracted increased attention (National Research Council, 1996; National Research Council, 2000; National Research Council, 2012). A considerable amount of research has focused on how to create and implement innovations aimed at improving teaching practices (Ertesvåg, 2014). Teachers play a crucial role in educational innovations (Bakkenes et al., 2010). The term innovative work behaviour has been used to refer to creating and implementing something new into the existing work (Ismail & Mydin, 2018; Pudjiarti, 2020). Studies on innovations in teaching have highlighted that the creation and implementation of innovations not only depend on an individual teacher's innovative work behaviour but also on the development of a collaborative innovation culture within school communities (Widmann, Mulder, 2018).

There are many possible factors explaining why some teachers are involved in innovative work activities while others prefer to repeat old ways of teaching. In addition to teacher characteristics, such as gender, age, personality and motivation, teaching experience and participation in professional development (PD) have also been highlighted as factors predicting teachers' innovative activities (Thurlings et al., 2015).

By using the TIMSS 2015 results, this study aims to explore how teaching experience and PD (duration and content) predict teachers' two collaborative innovative activities: working together to try out new ideas and sharing new ideas.

Theoretical background

Teachers' innovative work behaviour. The term innovation refers to new and, at least potentially, useful products and processes that help to improve existing situations or meet new challenges. According to Brewer, Tierney (2011), innovation has two components—the new idea and the change that results from the adoption of the new idea. Innovative work behaviour is the individual or collaborative contribution to accomplish activities related to innovations and includes various activities (Messmann & Mulder, 2014; Sun & Huang, 2019). A widely used definition for innovative work behaviour refers to three activities of individuals or groups in work environments: intentional idea generation, idea promotion and idea realisation (Janssen, 2004; Scott & Bruce, 1994). In a very similar way, other researchers (Rogers, 2003; Sun & Huang, 2019) have described a series of activities in which individuals generate novel ideas, solve practical problems at work and share new ideas with colleagues. Rogers' (2003) diffusion of innovation (RDI) theory describes the innovation process as comprising five stages: knowledge, persuasion, decision, implementation and confirmation. The first stage is cognitive-centred and is related to the generation of new ideas (Rogers, 2003).

To try out new ideas, workers seek information about an innovation, look for how to use it correctly and discuss how and why the innovation works. Idea championing becomes relevant once an idea has been generated, and championed ideas need to be implemented (De Jong, Den Hartog, 2010). The new idea is not approved at the implementation stage because this stage involves some degree of uncertainty (Rogers, 2003). The degree of uncertainty disappears at the last stage, confirmation, when workers seek support for innovation through the sharing of new ideas (Rogers, 2003).

According to Thurlings et al. (2015), Jansen's (2004) definition, originally developed in other professional fields, has been used in most studies on teachers' innovative work behaviour. Previous studies have found various factors that can predict the collaborative innovative activity of science teachers (Aldahmash et al., 2019; Baloche & Brody, 2017; Forte & Flores, 2014; Hargreaves, 2019; Jita & Mokhele, 2014; Waldron & McLeskey, 2010). Some of these factors, such as school-wide intervention, continuous PD, science STEAM content, professional self-development in collaborative activity and enquiry-based PD, have received considerable attention (Bantwini, 2019; Chai, 2019; Ertesvåg, 2014; Giles, 2018; Shernoff et al., 2017; Sims & Fletcher-Wood, 2021; Southerland et al., 2016).

Thurlings et al. (2015) revealed three groups of factors that influence teachers' innovative behaviour: demographic, individual and organisational. In addition, they found several individual factors that are positively associated with teachers' innovative behaviour, such as curiosity, various progressive attitudes and beliefs, motivational factors and competences, as well as negatively associated factors, such as traditional educational beliefs, habitual thinking and preferences for traditional teaching.

Establishment of hypotheses. RDI theory (2003) sees the innovation process as comprising five stages (knowledge, persuasion, decision, implementation and confirmation). According to RDI, all stages of the innovation process are connected by interpersonal local or cosmopolite channels. Seeking to evaluate complex community initiatives that focus on innovation leading to social change, a theory of change (ToC) was developed (Reinholz & Andrews, 2020). It is a tool that makes underlying assumptions explicit and uses the desired outcomes of an innovation as a mechanism to guide planning, implementation and evaluation. ToC articulates the specific interventions that will be used to try to achieve preconditions (Reinholz & Andrews, 2020). Each long-term precondition is paired with several indicators that describe the types of evidence needed to determine whether an outcome has been achieved in the short and long-term. In this article, we analyse the collaborative innovative activity of science teachers (long-term outcome). The indicators of this long-term outcome are the following: working together to try out new ideas and sharing new ideas. According to ToC, science teachers' innovative work activity is demonstrated through three interventions: PD content, PD duration and the extent of the teaching experience.

Sociocultural and activity theory approaches emphasise the collaborative nature of innovative work processes (Miettinen, 2014). Researchers applying sociocultural approaches have criticised the dominating research traditions of teachers' thinking and participation in the development of pedagogical innovations, which they view as too individualistic (Engeström, 1994). The collective nature of innovative work behaviour was demonstrated in a recent review of innovative work teams (Widmann et al., 2016). Several studies have shown the importance of collaboration in developing innovative use of technology in education (Mama, Hennessy, 2021; Whipp et al., 2005). Complementing RDI theory by using a sociocultural approach is important in this study because the TIMMS 2015 teacher questionnaire, which was used in the empirical analyses, focused on teachers' collaboration in developing and applying new ideas.

Many researchers have referred to the association between teachers' professional experience and collaborative innovative activity (Brekelmans et al., 2005; Ertesvåg, 2014; Forte & Flores, 2014; Goodnough, 2016; Hargreaves, 2005; Jita & Mokhele, 2014; Smith et al., 2020; Zulu & Bertram, 2019), but empirical studies have resulted in mixed findings (Thurlings et al., 2015). Teachers' professional experience, teaching skills and disposition influence educational practices (Karlberg & Bezzina, 2020; Kaya & Elster, 2019). In general, teachers gain their professional experience through a process that begins with preservice training and continues with in-service experience and training (EL-Deghaidy et al., 2015; Kaya & Gödek, 2016). Brekelmans et al. (2005) discussed the role of teachers' experiences in education and revealed two factors that influence a teacher's role in innovative activities: time for acquiring skills and enthusiasm about changes. Less experienced teachers might take a few years before acquiring the abilities required to cope with professional challenges and innovative activities, whereas teachers early in their careers might have more enthusiasm to overcome challenges using innovative practices (Brekelmans et al., 2005).

Hargreaves (2005) argued that experienced teachers are more relaxed and feel more comfortable in their professional activity than younger colleagues; however, towards the end of their career, they become resistant to change. Thus, teachers late in their careers are expected to lose energy and report less improvement than their younger colleagues. Hargreaves' (2005) findings suggest that less experienced teachers are more enthusiastic about change initiatives in their own classrooms, in which they believe they can best make a difference.

Ertesvåg (2014) investigated the effects of school-level factors and individual-level factors, such as perceived classroom learning environment and work experience, on teachers' collaboration in school development. The study showed that work experience had a positive effect, indicating that more experienced teachers reported a higher level of collaboration than less experienced teachers.

Some empirical studies on the factors predicting teachers' innovative work behaviour have shown that teaching experience is negatively associated with teachers' innovative work behaviour (Loogma et al., 2012; Yang & Huang, 2008). In their study on Estonian vocational teachers' attitudes and experiences of information communication and technology (ICT) use, Loogma et al. (2012) classified 21.6 percent of participants as innovators. They performed used logistic regression using various background variables to predict the probability of belonging to the innovator group. They found that teachers with five or less years of teaching experience had a 1.41 times greater probability of belonging to the innovator group than those with longer teaching careers.

According to the literature, PD has a positive effect on teaching effectiveness (Alshehry, 2018; Bilgin & Balbag, 2018; Chai, 2019; Shernoff et al., 2017).

Thurlings et al. (2015) found that teachers' positive attitudes towards the need for continuous learning and PD predict greater innovative behaviour, whereas the absence of a learning culture in the work environment is negatively associated with innovative work behaviour. The teachers who receive learning opportunities at their organisation tend to be keener to innovate than those who do not have these opportunities (Bada & Prasadh, 2019; Bourgonjon et al., 2013). Various forms of PD, such as active participation in in-service training and the number of workshops attended, have been found to have positive effects on innovative work behaviour (Donnelly et al., 2011; Mueller et al., 2008).

Some studies have indicated that PD activities require sufficient duration and that meaningful professional learning that translates to changes in practice cannot be accomplished in short, one-off workshops (Darling-Hammond et al., 2009; Desimone, 2009; Knapp, 2003; Weiss & Pasley, 2006). Research on the duration of science teachers' PD indicates that sustained duration has a positive effect on educational practices (Heller et al., 2012; Penuel et al., 2011; Wenglinsky, 2000).

However, there is a lack of research on the impact of PD participation on teachers' innovative behaviour have not specifically analysed how the different content areas of PD are related to teachers' innovative work behaviour.

So far, mixed findings have been found regarding the effects of teaching experience on teachers' innovative work activities. The study on teachers' experience have shown that increased work experience leads to improved teacher competence for only a few years after the beginning of their career (Hanushek, 2003), whereas the other study have shown longer positive effects of experience (Kini & Podolsky, 2016). Kini and Podolsky (2016) reported that experienced teachers support their colleagues more than less experienced teachers. In contrast, studies on teachers' active role in educational innovation have reported the opposite results: increased teaching experience is associated with decreased participation in innovative activities (Thurlings et al., 2015).

Hypothesis 1(H_1): We hypothesise that beginner teachers are more curious to try new ideas, whereas more experienced teachers contribute to innovation by sharing their experiences.

According to the literature, PD needs sufficient duration. Meaningful professional learning that translates into changes in practice cannot be accomplished through short PD courses (Darling-Hammond et al., 2009; Desimone, 2009; Knapp, 2003; Weiss & Pasley, 2006). Research on the duration of science teachers' PD has shown that sustained duration of PD participation has positive effects on educational practices (Penuel et al., 2011; Wenglinsky, 2000). Thurlings et al. (2015) showed that PD participation predicts teachers' innovative work behaviour.

Hypothesis 2 (H_2): We hypothesise that the length of the duration of formal PD participation is positively associated with innovative activities in science education.

To the best of our knowledge, no previous studies have directly focused on the relationship between different professional learning topics and teachers' innovative activities. However, studies on teaching effectiveness have emphasised pedagogical content knowledge (Baumert et al., 2010).

Hypothesis 3 (H_3): We hypothesise that PD participation focusing on pedagogical content knowledge predicts stronger collaborative innovative activities than PD focusing on the content knowledge of scientific disciplines.

Methods

Participants. In this study, we used teacher questionnaire data from the International Mathematics and Science Study for Japan, Lithuania and South Africa (TIMSS & PIRLS International Study Center, 2015). The sampling procedure is detailed in the methodological documents of the TIMSS study (Martin et al., 2016). The three countries were selected based on their science achievement scores (Martin et al., 2016). Japan is a high-achieving country in science when compared internationally. The achievement of Lithuanian students in TIMSS tests was close to the average of science achievements of the participating countries' students. South African students' achievements were at the lower end of the distribution. Practically all Japanese and Lithuanian science teachers teaching eighth graders had a bachelor's or higher degree, whereas many of the South African teachers did not have a university degree (TIMSS & PIRLS International Study Center, 2015). The number of participants and their demographic data are presented in Table 1.

There are substantial differences in the number of participants and teachers' demographic data among the samples from the three countries. Samples of Japanese and South African science teachers were much smaller than those of Lithuanian science teachers. The Japanese sample contained many more males than

Table 1 Descriptive statistics of science teachers' demographic data.

	Japan	Lithuania	South Africa
N	**170**	**965**	**331**
Age %			
Under 25	7.0	0.6	4.2
25–29	14.6	4.2	14.8
30–39	21.1	12.0	21.1
40–49	24.6	26.5	38.7
50–59	26.9	38.6	17.8
60 or more	4.7	14.3	2.1

females, whereas the Lithuanian sample contained more female than male teachers. In South Africa, there was a gender balance. Lithuanian teachers were the oldest among the three samples.

Measures. The TIMSS teacher questionnaire (Martin et al., 2016) includes questions about teachers' work experience, the duration of in-service PD and the topics related to PD courses.

Teaching experience. The TIMSS teacher questionnaire (Martin et al., 2016) included a question about teachers' work experience in terms of years of teaching (by the end of this school year, how many years will you have been teaching altogether?).

Participation in PD. The teacher questionnaire included a question about the amount of in-service PD and a detailed question about the PD topics (in the past two years, have you participated in PD in any of the following?). The following PD topics were presented in the questionnaire: (a) science learning, (b) science pedagogy/instruction, (c) science curriculum, (d) integrating information technology in science, (e) improving students' critical thinking or enquiry skills, (f) science assessment, (g) addressing individual students' needs and (h) integrating science with other subjects (e.g., mathematics and technology).

Innovative activities. This article focuses on revealing how PD content, duration and teaching experience predict science teachers' two collaborative innovative activities: working together to try out new ideas and sharing new ideas. According to RDI theory, these two activities correspond to the fourth and fifth stages of innovation. In the TIMSS 2015 teacher questionnaire, innovative activities did not have a separate scale, but were part of the general questions about teachers' collaboration (Martin et al., 2016). Two questions focused on innovative behaviour: How often do you have the following types of interactions with other teachers? 'Work together to try out new ideas' and 'Share what I have learned about my teaching experiences'.

With this in mind, we decided to apply ordinal logistic regression (OLR). In the first mathematical model, the dependent variable was the question: 'Work together to try out new ideas'. In the second model, the question was 'Share what I have learned about my teaching experiences'.

No psychometric data are available regarding the validity and reliability of these questions.

Data analysis. The possible responses for innovative work behaviour formed an ordinary scale (very often, often, sometimes, never or almost never). Thus, the OLR model (Polytomous Universal Model) was used to model how science teachers' collaborative innovative activity is predicted by PD participation, the content of PD and years of teaching experience. To estimate the odds ratios, we continued the analysis using the ordinal option of the generalised linear model of SPSS 25.

Table 2 Teaching experience.

Teaching experience in years	Japan	Lithuania	South Africa
Years of teaching (mean)	17.38	24.54	14.86
Years of teaching (SD)	12.09	10.83	10.06

Table 3 Percentage of science teachers' participation in PD.

TIMSS 2015 questions about professional development	Japan %	Lithuania %	South Africa %
Science content	74.9	64.0	78.1
Science pedagogy	74.9	55.9	54.0
Science curriculum	33.5	56.0	79.1
Integrating ICT	37.1	62.4	47.3
Improving students critical thinking or enquiry skills	24.6	44.7	54.3
Science assessment	29.2	60.3	69.5
Addressing individual students' need	29.2	52.0	51.4

Results

Descriptive results. The TIMSS 2015 questionnaire provided data about the science teachers' teaching experience and their PD participation in terms of the duration and content of formal PD. The mean number of science teachers' years of teaching varied across the three countries (Table 2). According to TIMSS 2015 data, the greatest mean of teaching years was observed for the Lithuanian sample.

The frequencies of teachers' PD participation with various contents are presented in Table 3.

The frequency of having science content as the topic of professional learning was high in all three samples. In addition, compared to the teachers of the other two countries, Japanese teachers reported greater participation in science pedagogy PD courses but clearly lesser participation in courses on individual students' needs.

Lithuanian science teachers were most often involved in PD related to science content and integrating ICT and less involved in PD related to improving students' critical thinking or enquiry skills. South African teachers most often participated in PD related to science curriculum and science content, and less in PD related to integrating ICT (Table 3).

Lithuanian and South African teachers were involved in longer durations of PD than Japanese teachers (Table 4). Table 5 presents the distribution of teachers' answers to the question about trying new ideas. As shown in the table, the frequencies of the category 'very often' are rather small in the Japanese and Lithuanian samples. To avoid too many small or zero cell frequencies in the OLR analysis, we recoded the variable by combining the categories 'very often' and 'often'.

The teachers' answers to the question about sharing experiences are presented in Table 6.

In all samples, the frequencies of 'never or almost never' answers were quite small. To avoid too many small or zero cell frequencies in the OLR analysis, we recoded the variable by combining the categories 'sometimes' and 'never or almost never'.

Predicting science teachers' collaborative innovative activities. Cumulative OLRs with proportional odds were used to predict the two dependent variables dealing with collaborative innovative

Table 4 Duration of PD of science teachers in the last 2 years: Japan, Lithuania and South Africa.

Duration	Japan %	Lithuania %	South Africa %
None	18.1	2.9	6.4
Less than 6 h	26.9	7.3	19.3
6–15 h	27.5	31.5	29.6
16–35 h	19.9	30.3	18.6
More than 35 h	7.0	28.0	26.0

Table 5 Frequencies of answers to the variable 'Work together to try out new ideas' (TRY) in Japan, Lithuania and South Africa.

Country	Very often %	Often %	Sometimes %	Never or almost never %
Japan	3.5	21.2	56.5	18.2
Lithuania	5.2	27.2	62.1	5.5
South Africa	18.0	37.6	37.0	7.4

Table 6 Distribution of answers to the variable 'Share what I have learned about my teaching experiences' (SHARE) in Japan, Lithuania and South Africa.

Country	Very often %	Often %	Sometimes %	Never or almost never %
Japan	6.4	43.3	43.9	5.9
Lithuania	10.0	44.9	39.3	1.3
South Africa	27.2	41.1	27.5	2.7

activity and the independent variables (teaching experience and the amount and content of PD [CPD]). The following formulae were used separately for the datasets obtained from different countries:

$$\mathrm{TRY} = f\left(\mathrm{DPD}, \mathrm{CPD_i}, \mathrm{PE}\right) \quad (1)$$

$$\mathrm{SHARE} = f\left(\mathrm{DPD}, \mathrm{CPD_i}, \mathrm{PE}\right) \quad (2)$$

where TRY and SHARE indicate two innovative work behaviour variables, DPD indicates the duration of PD (in h), and PE indicates the years of teaching. The variable $\mathrm{CPD_i}$ comprises different PD content: science content, science pedagogy, science curriculum, integrating ICT, improving students' critical thinking or enquiry skills, science assessment and addressing individual students' needs.

The OLR process involves checking a few assumptions. The dependent variable should be measured at the ordinal level, and predictors are continuous or categorical variables. For an ordinal dependent variable TRY with three categories, equations were created, each with a different intercept but the same b coefficients (slopes) for the predictor variables. This means that the effects of the independent variables were the same for each level of the dependent variable. The proportional odds assumption was tested with the likelihood ratio test (test of parallel lines).

According to the third assumption, one or more independent variables must be continuous, ordinal or categorical (including dichotomous variables). However, ordinal independent variables must be treated as either continuous or categorical. Independent variables (DPD, CPD and PE) were used in the analysis as covariates or factors. The continuous variable—PE—was assigned to covariates. The CPD variables were dichotomous (no/yes) and were added as factors to the analysis. The originally ordinal variable regarding the amount of PD (DPD) was transformed into two categories: (1) short PD (up to 15 h) and (2) long PD (more than 16 h) (Table 3). The categorical variable DPD was assigned as a factor in the OLR model.

Multiple linear regressions were conducted to test the multicollinearity of the predictor variables. For the datasets of all three countries, the variance inflation factors were low (between 1.018 and 2.300), showing that the independent variables were not highly correlated with each other.

The first set of ORL models was run to predict science teachers' frequency of trying out new ideas. The assumption of proportional odds was tested with a parallel lines test, and as shown in Table 7, this assumption was met in all three samples ($p > 0.05$).

The model fitting information obtained from the comparison of a model without any explanatory variable (the baseline or 'intercept-only' model) and the one with all explanatory variables (the 'final' model) is presented in Table 8. The significant chi-squares ($p < 0.05$) in all three samples indicate that the final model yielded significant improvement over the baseline intercept-only model.

The chi-square values of the deviance goodness-of-fit test showed that the observed data were consistent with the fitted model for the Japanese $\chi^2(287) = 280.041$, $p = 0.604$; Lithuanian $\chi^2(938) = 1350.578$, $p = 0.999$; and South African $\chi^2(465) = 431.465$, $p = 0.865$ data.

Wald's statistics for the OLR model of Japanese teachers showed that teaching experience was the only significant predictor of the probability of trying out new ideas. For every increasing year of experience, the odds of trying out new ideas were 1.036 (95% CI, 1.009–1.064) times greater ($\chi^2(1) = 6.647$, $p = 0.010$).

Wald's statistics of the OLR model of Lithuanian teachers showed that two of the PD content areas—science curriculum training and improving students' critical thinking—were significant predictors of the probability of trying out new ideas. However, the teachers' professional experience and the duration of PD participation were not significant predictors of this innovative activity. The odds of trying out new ideas for Lithuanian science teachers who had science curriculum as a PD content was 1.501 (95% CI, 1.119–2.014) times that of the teachers who did not participate this PD content ($\chi^2(1) = 7.361$, $p = 0.007$). The odds of trying out new ideas for the Lithuanian teachers who had students' critical thinking or enquiry skills as a PD content area was 1.578 (95% CI, 1.190–2.092) times that of teachers who did not have this PD content ($\chi^2(1) = 10.051$, $p = 0.002$).

Based on Wald's statistics of the OLR model for the South African data, only one of the PD content areas—addressing individual students' needs—was a significant predictor of the teachers' frequency of trying out new ideas in collaboration with other teachers. The odds of trying out new ideas for the South African science teachers who had addressed individual student needs as a PD content subject was 2.216 (95% CI, 1.173–4.189) times that of the teachers who did not have this PD content ($\chi^2(1) = 6.002$, $p = 0.014$).

The second set of ORL models was run to predict science teachers' frequency of sharing experiences. The assumption of proportional odds was tested with a parallel lines test, and as seen in Table 9, this assumption was met in all three samples ($p > 0.05$).

The model fitting information based on the comparison of a model without any explanatory variables (the baseline or 'intercept-only' model) against the one with all explanatory

Table 7 Parallel lines test of the models' predicting frequency of trying out new ideas.

Country	Model	-2 log likelihood	Chi-square	df	Sig.
Japan	Null hypothesis	291.602			
	General	283.484	8.118	9	0.522
Lithuania	Null hypothesis	1416.287			
	General	1412.902	3.384	9	0.947
South Africa	Null hypothesis	455.503			
	General	449.899	5.604	9	0.779

Table 8 Model fitting information of the models predicting frequency out of trying out new ideas.

Country	Model	-2 log likelihood	Chi-square	df	Sig.
Japan	Intercept only	312.908			
	Final	291.602	21.306	9	0.011
Lithuania	Intercept only	1463.302			
	Final	1416.287	46.015	9	0.001
Shout Africa	Intercept only	498.798			
	Final	455.503	43.295	9	0.001

Table 9 Parallel lines test of the models' predicting frequency of sharing experiences.

Country	Model	-2 log likelihood	Chi-square	df	Sig.
Japan	Null hypothesis	264.639			
	General	251.00	9.538	9	0.389
Lithuania	Null hypothesis	1650.520			
	General	1645.583	4.937	9	0.840
South Africa	Null hypothesis	574.169			
	General	567.274	6.894	9	0.648

Table 10 Model fitting information of the models' predicting frequency of sharing experiences.

Country	Model	-2 log likelihood	Chi-square	df	Sig
Japan	Intercept only	282.605			
	Final	264.639	17.966	9	0.036
Lithuania	Intercept only	1681.257			
	Final	165020	30.738	9	0.001
Shout Africa	Intercept only	598.559			
	Final	574.169	24.390	9	0.004

Link function: Logit

variables (the 'final' model) is presented in Table 10. The significant chi-squares ($p < 0.05$) indicate that the final model yielded significant improvement over the baseline intercept-only model in all three samples.

The chi-square values of the deviance goodness-of-fit test showed that the observed data were consistent with the fitted model for the Japanese $\chi^2(287) = 253.007$, $p = 0.926$ and Lithuanian $\chi^2(1509) = 1559.629$, $p = 0.178$ data but not the South African data ($\chi^2(447) = 538.936$, $p = 0.012$). However, the goodness-of-fit results were problematic to interpret in models including cells with zero frequencies. An alternative test, Pearson's goodness-of-fit measure, indicated a good fit ($\chi^2(447) = 513.515$, $p = 0.067$).

Wald's statistics of the OLR model of Japanese teachers showed that teaching experience was a significant predictor of the probability of sharing experiences with other teachers. For every increasing year of experience, the odds of sharing experiences were 1.038 (95% CI, 1.010–1.067) times greater ($\chi^2(1) = 6.881$, $p = 0.009$). None of the PD variables were significant predictors of Japanese science teachers' frequency of sharing experiences with other teachers.

Wald's statistics of the OLR model for Lithuanian teachers showed that two of the PD content areas—science curriculum training and improving students' critical thinking—were significant predictors of the probability of sharing experiences with other teachers. The odds of sharing experiences for Lithuanian science teachers who had a science curriculum as a PD content area was 1.493 (95% CI, 1.136–1.962) times that of teachers who did not have this PD content ($\chi^2(1) = 8.287$, $p = 0.004$). The odds of sharing experiences for the Lithuanian teachers who had students' critical thinking or enquiry skills as a PD content area was 1.404 (95% CI, 1.078–1.827) times that of teachers who did not have this PD content ($\chi^2(1) = 6.356$, $p = 0.012$).

Wald's statistics of the OLR model of the data for South Africa showed that addressing individual student needs was a significant predictor of the frequency of sharing experiences with other teachers. The odds of sharing experiences for South African science teachers who had addressed individual student need as a

PD content area was 2.107 (95% CI, 1.162–3.822) times that of teachers who did not have this PD content ($\chi^2(1) = 6.024$, $p = 0.014$).

Discussion

In this study, we conducted a secondary analysis of the TIMSS 2015 science teachers' questionnaire data from three countries: Japan, Lithuania and South Africa. The aim was to validate whether teachers' experience and PD participation predict their collaborative innovative activity in these countries using varying students' achievement in science and teachers' competences. Two questions of the TIMSS questionnaire dealt with collaborative innovative activity and focused on interaction when trying new ideas and sharing experiences with other teachers. No clear common trend was observed in the results from the three countries. In Japan, teaching experience was a positive predictor of both aspects of teachers' collaborative innovative activity. In Lithuania, both aspects of innovative behaviour were predicted by PD participation focusing on the science curriculum and enhancing students' critical thinking. In the South African sample, both aspects of teachers' collaborative innovative activity were predicted by PD participation focusing on the individual needs of students. The duration of PD did not predict innovative activities in the Japanese or Lithuanian samples, and in the South African sample, PD duration was negatively related to teachers' frequency of sharing experiences with other teachers.

Teaching experience and innovative activity. In this study, Japanese teachers' work experience was positively related to the frequency of both aspects of collaborative innovative activities, but in the Lithuanian and South African samples, there was no relationship between increased experience and innovative activities. The results did not support our hypotheses regarding the associations between work experience and the two aspects of innovative activity analysed in this study.

There were substantial differences in teachers' mean age and their teaching experience among the samples from the three countries. Lithuanian teachers were clearly older and had longer careers than Japanese and South African teachers. The South African teachers were the youngest with the least amount of teaching experience. The literature has reported mixed results regarding the effects of teaching career length on innovative behaviour. In general, teacher competence seems to improve during the first or even second decade of experience (Kini & Podolsky, 2016), and experienced teachers report a greater level of collaboration (Ertesvåg, 2014) then beginning teachers; however, some studies have indicated that long teaching careers are related to decreased innovativeness (Thurlings et al., 2015). Studies in other fields have indicated that the relationship between work experience and innovative behaviour is different in different cultural contexts (Ruiu & Breschi, 2019).

PD duration and innovative activities. The study results do not support our hypothesis about the association between PD duration and innovative activity. Most studies on teachers' PD have indicated that duration is an important feature of PD programmes (Darling-Hammond et al., 2017; Desimone, 2009; Knapp, 2003; Weiss & Pasley, 2006). However, a clear threshold has not yet been defined for the duration of effective PD models (Darling-Hammond et al., 2009).

In this study, there was a large variation in the duration of teachers' PD participation among the three countries. Lithuanian and South African science teachers reported longer participation in professional learning than Japanese teachers. Almost 20 percent of Japanese teachers did not undergo any PD during the last two years, whereas more than 25 percent of Lithuanian and South African teachers reported that they underwent more than 35 h of PD during that time. In previous studies, PD participation predicted greater innovative behaviour among teachers (Thurlings et al., 2015). However, in the TIMSS 2015 teacher questionnaire data, we could not find this relationship. On the contrary, there was a negative relationship between PD duration and innovative behaviour in the South African sample. One possible explanation for this is the inadequate implementation of teachers' PD, which does not lead to sustainable results (Antoniou, Kyriakides, 2013; Riley-Tillman, Eckert, 2001). It is also possible that the two self-report questions of the TIMSS teacher questionnaire did not capture teachers' innovative behaviour in a similar way to the measures used in earlier studies, which have shown the relationship between PD and innovative behaviour.

PD content and innovative activities. None of the PD content areas were significant predictors of innovative activities in the Japanese sample. In the Lithuanian sample, science curriculum and students' critical thinking and enquiry skills were topics that predicted both aspects of collaborative innovative activities, whereas in the South African sample, addressing students' individual needs was a predictive PD topic for both aspects of innovative activities. There was no clear pattern of how PD content predicts innovative activities. However, the results partly support our hypothesis regarding the association between PD content and innovative activity. Previous studies have shown that science teachers' content knowledge about scientific topics is a necessary prerequisite for good teaching, but teachers' pedagogical content knowledge is an even more important predictor of teaching effectiveness (Baumert et al., 2010). In this study, all PD content that predicted collaborative innovative activities was related to pedagogical content knowledge. This is in line with previous studies focusing on teachers' professional learning content (Aldahmash et al., 2019; Campell, 2019; Chai, 2019; Chaudhuri et al., 2019; Moore et al., 2021). However, there were substantial differences among the three countries. No causal claim can be made on the basis of these relationships. We do not know if all PD content was similarly available to all teachers in all three countries or if the teachers had the opportunity to choose the PD courses in which they wanted to participate. It is also possible that teachers with a strong tendency towards innovative behaviour actively chose certain PD topics in certain historical and sociocultural situations.

Limitations. The limitations of this study should be considered when interpreting the results. There were no subscales of teachers' innovations based on several questions in the TIMSS 2015 questionnaire, but the measure of collaborative innovative activities was based on two separate ordinal items. Thus, the reliability of these items could not be checked, and no previous validity or reliability information was available in the TIMSS methodology documents. The two questions covered only part of the aspect of innovative work behaviour described in current theories. Thus, more comprehensive data collection instruments are needed in future studies. Self-report scales also have limitations, and other methods, such as classroom observations, would result in more reliable findings.

In addition, there were cultural differences in interpreting the questions and using the rating scales. The selection of a few countries was also problematic. To have greater variation, we selected one example each from countries representing high, average and low student achievements in the TIMSS study. However, this does not mean that the results related to these achievement levels can be generalised to other countries. In the future, we can merge datasets from several countries representing different student achievement levels. Because of the nature of the data, all associations were correlative, and no causal conclusions could be drawn.

The TIMSS teacher questionnaire measured the duration of PD without considering the form of PD realisation. For example, the duration of a one-day PD workshop can be accurately measured in hours, but the accurate estimation of the duration of sustained development is much more difficult because of the informal learning taking place within the classroom context between formal sessions. 'By promoting learning over time, both within and between sessions, PD that is sustained may lead to many more hours of learning than is indicated by seat time alone' (Darling-Hammond et al., 2017, p. 16). However, the findings of our study encourage further research on the role of PD duration in collaborative innovative activity among science teachers. It would be interesting to investigate whether the duration of PD is related to teachers' innovative activity when different PD forms are considered.

In order to obtain an acceptable model fit, we tested a mathematical model in which the amount of PD was transformed into two categories: (1) short PD (up to 15 h) and (2) long PD (more than 16 h). According to this model, we found that the amount of PD was not a significant predictor of science teachers' innovative activities in the Japanese and Lithuanian samples and was a negative predictor in the South African sample. Our study does not necessarily contradict previous studies that PD needs sufficient duration or that meaningful professional learning that translates into changes in practice cannot be accomplished with short PD courses (Darling-Hammond et al., 2009; Desimone, 2009; Knapp, 2003; Weiss & Pasley, 2006). However, our study calls for testing alternative mathematical models by using different categories of PD amounts.

Conclusions and educational implications

We examined two activities of science teachers' innovative behaviour, trying and sharing new ideas, which are related to different aspects of school development. The study results indicated somewhat similar patterns of predictors of both aspects of innovative behaviour; however, there were substantial differences among the Lithuanian, Japanese and South African teachers. The results highlighted the role of PD focusing on pedagogical content knowledge as a predictor of science teachers' innovative behaviour. Adequate proficiency of content knowledge in science domains is an important prerequisite for innovative teaching, but as shown by Baumert et al. (2010), pedagogical content knowledge is a stronger predictor of teaching effectiveness.

The results also indicate that PD duration alone is not a sufficient predictor of innovative activities. The content training and the ways in which science teachers' PD is organised might be more important than just the duration of formal in-service training events. In order to improve the innovative performance of science teachers, more emphasis should be placed on the content of PD and on the methods used in teachers' in-service training.

Our study revealed that in only one case (Japanese), the work experience of science teachers was positively related to the frequency of both collaborative innovative activities: trying out new ideas and sharing. The duration of work experience of Japanese science teachers was greater than those from South Africa and less than those from Lithuania. In order to understand the preconditions for innovative science education and cooperation in implementing innovations in educational practice, it is not enough to focus on the relationship between the amount of teaching experience and innovative activity on average. Expert research has shown that increasing work experience leads to increasing expertise among some workers, whereas others' careers can be described as arrested expertise development (Ericsson, 2018). In a similar way, it is important to focus on the varying professional learning trajectories and analyse how they are related to teachers' innovative activities. This would also help to develop PD programmes so that they better meet the specific needs of various teacher groups.

Data availability

The datasets analysed during the current study are publicly available at: https://timssandpirls.bc.edu/timss2015/international-database/

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Author contributions

Conceptualisation, PP; methodology, PP and EL; software, PP; validation, PP and EL; formal analysis, PP and LK; investigation, EL, PP and LK; data curation, PP; writing—original draft preparation, PP and EL; writing—review and editing, LK; visualisation, PP and EL. All authors read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval

The research was carried out following the provisions which underline the basic principles of professionalism and ethics of research, approved by the Resolution No. SEN-N-17 of the Senate of Vytautas Magnus University of 24 March 2021. The study was conducted in accordance with the principles of reliability, integrity, respect, and accountability and with the provisions of point 23, which define the cases in which the investigator is required to submit to the evaluation committee his/her research plan for the validation of compliance with the professionalism and ethics of the research.

Informed consent

In the case of this study, written informed consent is not necessary, since our research is based on a secondary data analysis.

Additional information

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