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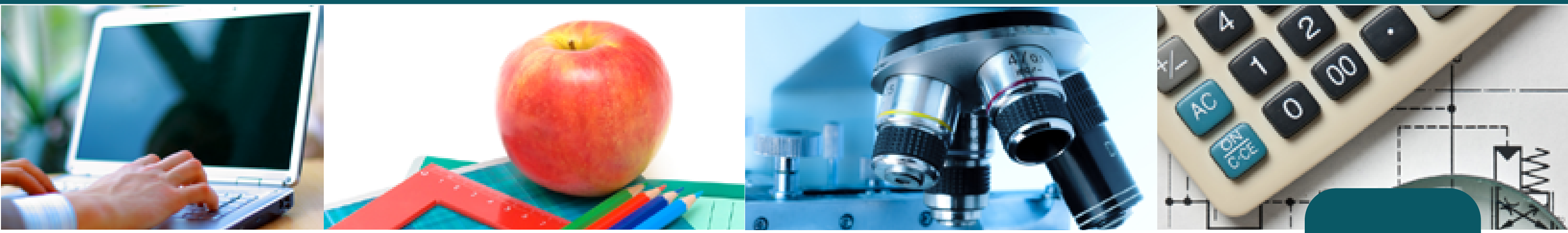

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Does How Science Is Taught Relate to Science Achievement in PISA?

Science and technology are omnipresent in Canadians' everyday lives. Primary and secondary school programs try to support the development of students' science literacy throughout their compulsory education, and they attempt to nurture the interest of students planning to pursue the study of science and technology beyond high school.

In order to meet these objectives, teachers organize a variety of learning and assessment activities, within a variety of school settings. According to the Organisation for Economic Co-operation and Development (OECD), teaching and learning activities are the strongest predictors of students' skills, regardless of their characteristics (Mostafa, Echazarra, & Guillou, 2018). Science teaching quality is also thought to be a significant determinant in students' attitudes toward science in school and subject choice (Osborne, Simon, & Collins, 2003).

According to Klieme, Pauli, and Reusser (2009), teaching quality depends on: a supportive, student-oriented climate; clear, structured educational management; and cognitive activation that stimulates learning. This paper explores the last two aspects in science classrooms based on the responses of 15-year-old students to the contextual questionnaires used in the Programme for International Student Assessment (PISA). First, we will look at students' perception of teacher-directed instruction and enquiry-based science teaching. The former are part of structured management activities, and the latter are associated with cognitive activation activities (OECD, 2017). More specifically, we will attempt to determine, on the one hand, how provincial education systems differ in these teaching-related aspects, and, on the other hand, whether there are differences in perception between girls and boys and between students in French-language school systems and those in English-language school systems. Then, we will explore the effect of these teaching practices on students' science outcomes and on attitudes toward science.

Research brief developed for the Council of Ministers of Education (CMEC) by
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PISA is an international assessment that measures the knowledge and skills of 15-year-old students in three domains: reading, mathematics, and science. Every three years since 2000, PISA has focused on one of these domains in greater detail. Accordingly, science literacy was the major domain for the assessment in 2006 and 2015 (https://www.oecd.org/pisa/). It will be the focus again in PISA 2025; the results will be available in 2026.

All 10 provinces participate in PISA, each with a sample that produces statistically valid results for the entire province.

Teacher-directed instruction and enquiry-based science teaching

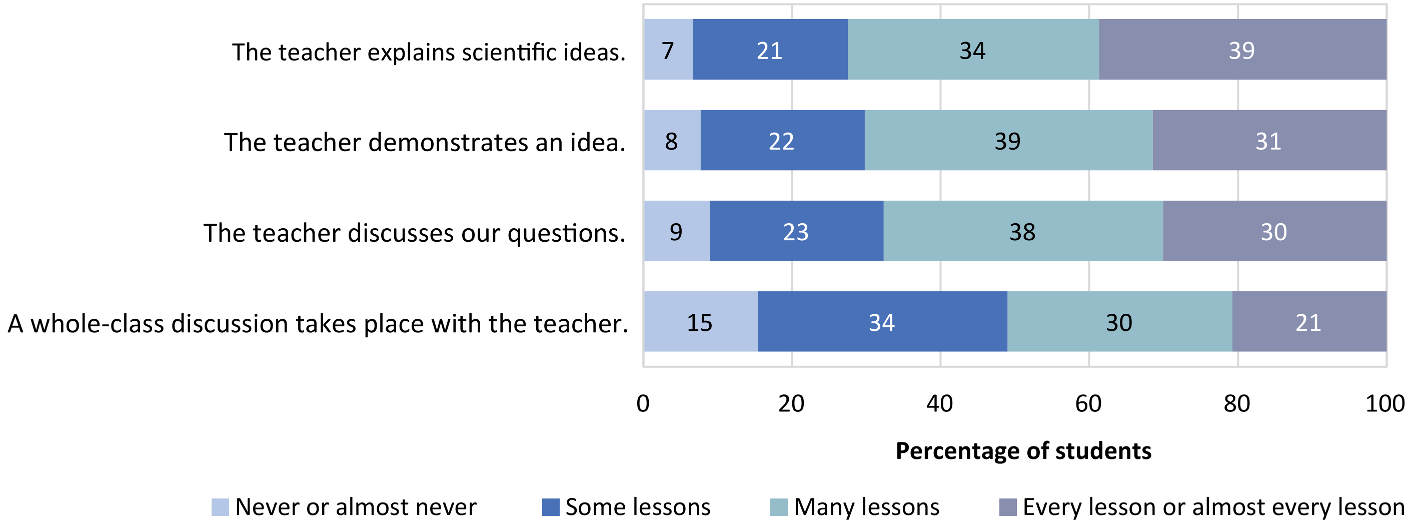
Science teaching should not only allow young people to understand and act with confidence, but also help foster and maintain positive attitudes toward science. Some teaching practices are associated with higher performance, while others are associated with more positive attitudes; some teaching practices may combine these advantages (Savelsbergh, Prins, Rietbergen, Fechner, Vaessen, Draijer, & Bakker, 2016). The following sections will discuss practices associated with teacher-directed instruction and those associated with enquiry-based science teaching, which has gained traction over the past two decades. Teacher-directed instruction is thought to be associated with passive learning, where students tend to use strategies like memorization, whereas enquiry-based teaching involves learning strategies like analysis and interpretation (Furtak, Seidel, Iverson, & Briggs, 2012).

Teacher-directed instruction

It is common for teachers to use structured learning to varying degrees in their teaching practices. Along these lines, PISA's definition of teacher-directed instruction includes practices like explanation and demonstration of scientific concepts, discussion of students' questions, and classroom debates (OECD, 2016).

In PISA 2015, students were asked to respond to four items concerning how science was taught in their classroom. Figure 1 shows the four items that constitute the teacher-directed instruction index. The questionnaire items for this index are presented according to decreasing frequency of the use of each technique in the science classroom. Close to 40 percent of students reported that the method most frequently used by their teachers was to explain scientific ideas, whereas whole-class discussion was the least frequently used method.

Figure 1 **Percentage of students by their responses to questionnaire items related to index of teacher-directed instruction, PISA 2015**

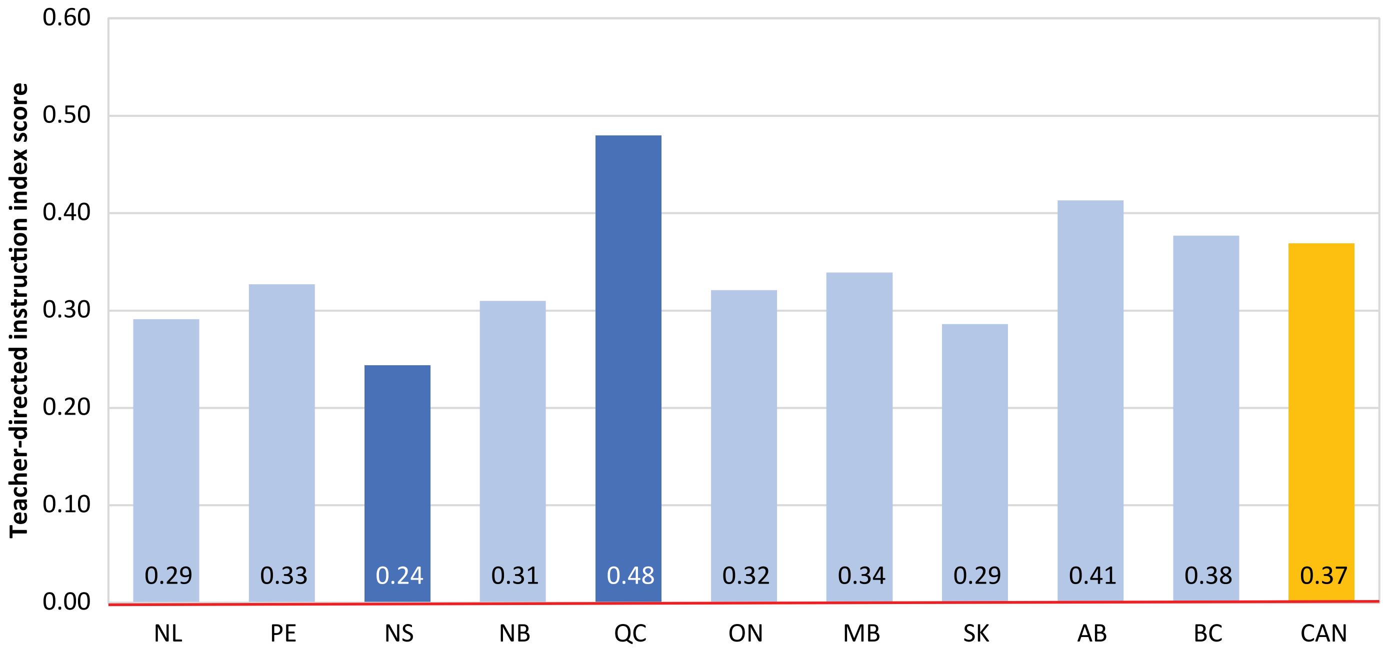


The average index of teacher-directed instruction varies from 0.24 in Nova Scotia to 0.48 in Quebec (Figure 2). The differences between the averages of these two provinces and the Canadian average mean that students in Nova Scotia reported that they are slightly less exposed to teacher-directed instruction practices compared to Canadian students on average, while those in Quebec reported that they are slightly more exposed to it than the average. In the other provinces, there is no statistically significant difference in the indices compared to the Canadian average.

Indices of teaching practices in PISA 2015

When responding to the questionnaire, students were encouraged to think about the science course they were taking the year they wrote the test. The students' responses were combined to create an index, in such a way that, in OECD countries, the index has an average of 0 and a standard deviation of 1. Positive values indicate that the students in a province responded more positively to the items compared to the OECD average.

FIGURE 2 Results for the teacher-directed instruction index, PISA 2015



Note: Darker shades denote significant difference compared to Canada. Red line denotes the OECD average.

There was no statistically significant difference between boys and girls in the index of teacher-directed instruction, except in Nova Scotia (Table 1). An examination of averages based on testing language shows differences in the majority of the seven provinces where the sample was big enough to present separate results for each language system. In Nova Scotia, New Brunswick, Quebec, Ontario, and Manitoba, students in French-language systems are more likely than those in English-language systems to report teacher-directed instruction, as defined by PISA, being used in the classroom. It seems that direct instructional strategies, associated with teacher-directed instruction, require teachers to have advanced language skills; teachers in French-first-language and English-first-language contexts use different sets of language skills, but these differences do not appear to be significant from one language context to the other (CMEC, 2013).

Table 1 Results for teacher-directed instruction index, by gender and language of the school system, PISA 2015

	Index score, by gender					Index score, by language of the school system				
	Girls		Boys		Difference (G–B)	Anglophone		Francophone		Difference (A–F)
	Index score	Standard error	Index score	Standard error		Index score	Standard error	Index score	Standard error	
NL	0.30	0.04	0.28	0.05	0.02	--	--	--	--	--
PE	0.34	0.08	0.32	0.10	0.02	--	--	--	--	--
NS	0.18	0.03	0.32	0.06	-0.14*	0.23	0.04	0.65	0.12	-0.42*
NB	0.31	0.04	0.31	0.05	-0.01	0.19	0.04	0.65	0.07	-0.47*
QC	0.50	0.04	0.46	0.05	0.04	0.30	0.05	0.50	0.04	-0.20*
ON	0.29	0.03	0.35	0.03	-0.06	0.31	0.02	0.47	0.04	-0.15*
MB	0.30	0.04	0.37	0.06	-0.07	0.32	0.04	0.60	0.08	-0.27*
SK	0.26	0.04	0.31	0.06	-0.05	--	--	--	--	--
AB	0.37	0.05	0.46	0.03	-0.09	0.41	0.03	0.36	0.40	0.05
BC	0.34	0.05	0.42	0.04	-0.08	0.38	0.04	0.31	0.24	0.07
CAN	**0.35**	**0.03**	**0.39**	**0.04**	**-0.04**	**0.33**	**0.01**	**0.51**	**0.04**	**-0.17**

*Significant difference within Canada or province.
Note: Because Newfoundland and Labrador, Prince Edward Island, and Saskatchewan did not oversample students by language, results for only English-language schools are available for these provinces.

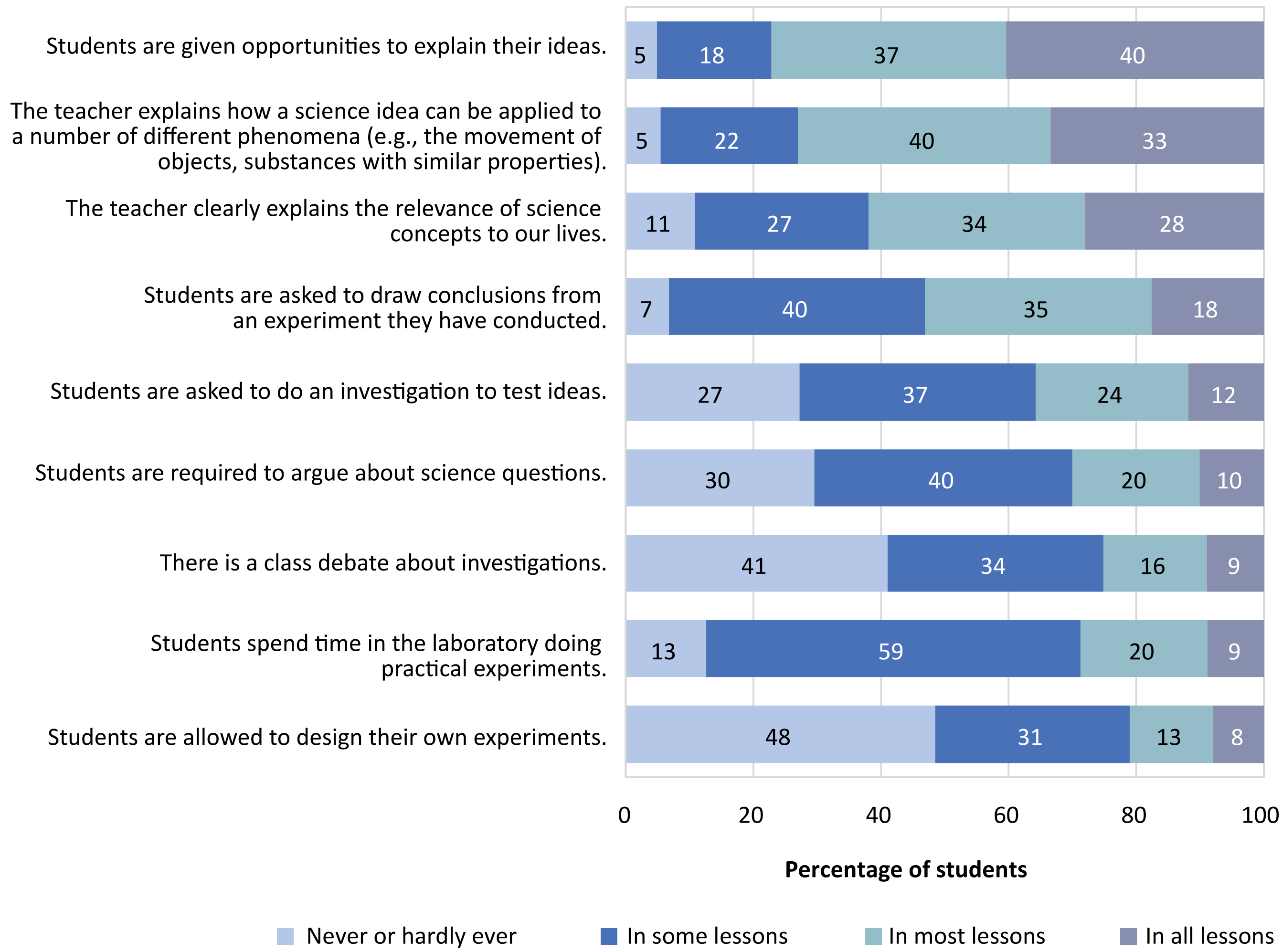
Enquiry-based learning

The importance of enquiry as a teaching practice has been reaffirmed and maintained in curricula under various names (Hasni, Belletête, & Potvin, 2018; OECD, 2017). Its objectives, methods, and outcomes continue to be the subject of research around the world. Enquiry-based teaching practices appear to have a positive effect on performance, according to Furtak et al. (2012), but this effect is greater when instruction is guided by the teacher. These practices also seem to foster positive attitudes toward science and the development of critical attitudes that students can use in other subjects (Hattie, 2012).

Enquiry-based practices are associated with cognitive activation — in other words, teaching strategies that encourage students to think to find solutions and to pay attention to the methods they are using to arrive at an answer rather than simply focusing on the answer (National Foundation for Educational Research, n.d.). In PISA 2015, this dimension of cognitive activation includes a large variety of approaches, ranging from open-ended and independent enquiry to a question-based approach that is more structured by the teacher. It was measured using a subgroup of nine items administered initially in PISA 2006 and later in PISA 2015. Students were asked to indicate how often the nine activities shown in Figure 3 occur during their school science courses. The most frequent activities are those that happen in the classroom and involve discussions among students and with the teacher, undoubtedly due in part to how easy it is to start doing this and the very few resources it requires. Activities that occur in the laboratory — more specifically, those that involve a high level of self-sufficiency on the part of students — are less frequent.

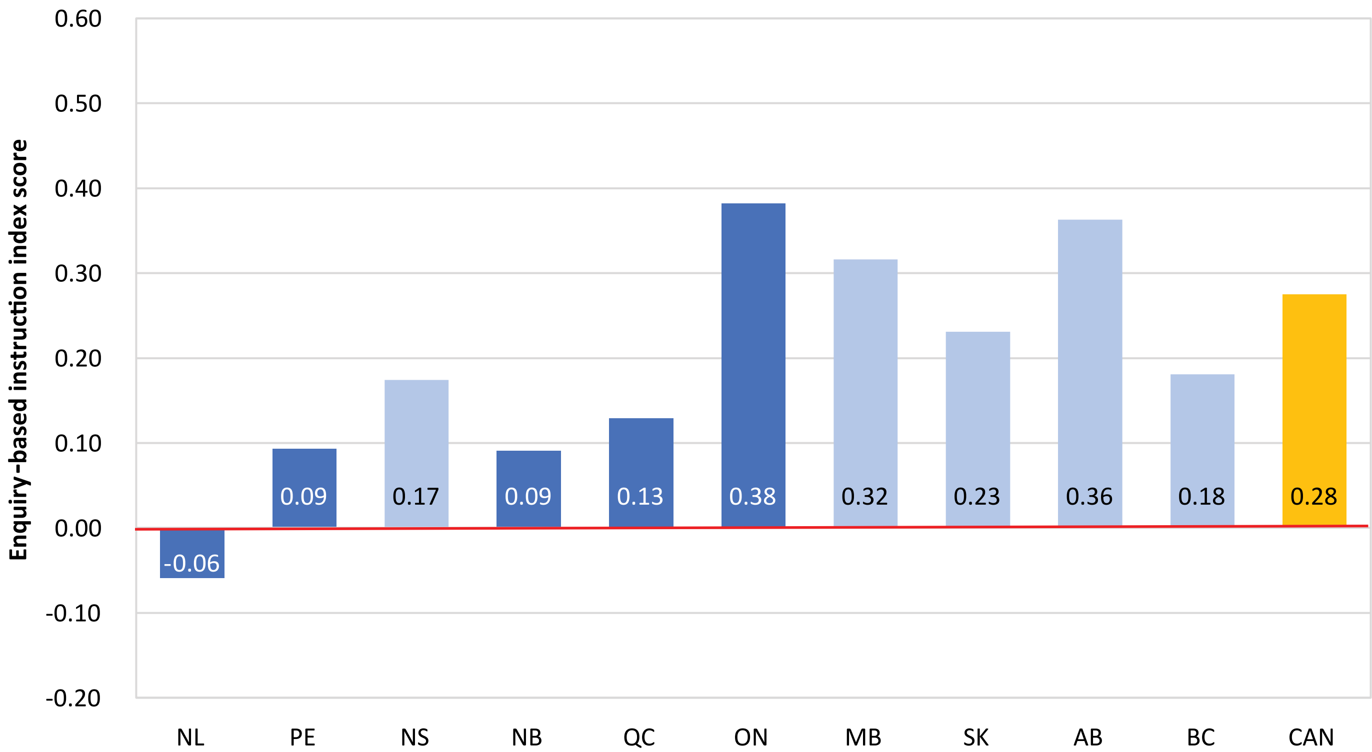
The index of enquiry-based teaching combines the answers to the nine questions in PISA 2015 in order to determine how often students report that they are exposed to this kind of practice (Figure 3).

FIGURE 3 Percentage of students by their responses to questionnaire items related to the enquiry-based instruction index, PISA 2015



Provincial averages for this index are shown in Figure 4. The provincial indices are above the OECD average except in Newfoundland and Labrador and Prince Edward Island, where there is no difference with the OECD average. In terms of Canada as a whole, the indices for Newfoundland and Labrador, Prince Edward Island, New Brunswick, and Quebec are statistically lower than the Canadian average, while the Ontario index is higher.

FIGURE 4 Results for the enquiry-based instruction index, PISA 2015



Note: Darker shades denote significant difference compared to Canada. Red line denotes the OECD average.

The indices of enquiry-based instruction, when analyzed by language of the school system, in the seven provinces where the sample permitted this type of analysis, differ statistically in New Brunswick and Manitoba and at the pan-Canadian level (Table 2). In all provinces, boys responded more positively than girls to questions associated with the index of enquiry-based instruction. In Newfoundland and Labrador, the average index for girls is statistically lower than the OECD average. Some studies (Krapp & Prenzel, 2011) underscore that significant differences may appear between boys and girls in terms of interest, depending on the type of teaching used in the classroom. The fact that enquiry-based teaching generates a different amount of interest depending on gender could partially explain the differing perceptions of how frequently this type of activity occurs.

Table 2 Results for the enquiry-based instruction index, by gender and language of the school system, PISA 2015

	Index score, by gender					Index score, by language of the school system				
	Girls		Boys		Difference (G–B)	Anglophone		Francophone		Difference (E–F)
	Index score	Standard error	Index score	Standard error		Index score	Standard error	Index score	Standard error	
NL	-0.16	0.04	0.05	0.06	-0.21*	--	--	--	--	--
PE	-0.07	0.07	0.27	0.10	-0.34*	--	--	--	--	--
NS	0.08	0.04	0.28	0.06	-0.21*	0.17	0.04	0.30	0.12	-0.13
NB	-0.03	0.04	0.22	0.04	-0.25*	0.05	0.04	0.22	0.05	-0.18*
QC	0.01	0.04	0.26	0.04	-0.25*	0.14	0.04	0.13	0.04	0.01
ON	0.27	0.04	0.49	0.03	-0.22*	0.38	0.03	0.43	0.04	-0.05
MB	0.16	0.04	0.48	0.06	-0.32*	0.30	0.04	0.57	0.08	-0.27*
SK	0.16	0.05	0.30	0.09	-0.14*	--	--	--	--	--
AB	0.25	0.04	0.48	0.05	-0.23*	0.36	0.04	0.39	0.19	-0.02
BC	0.08	0.06	0.30	0.05	-0.22*	0.18	0.04	-0.07	0.18	0.25
CAN	**0.16**	**0.02**	**0.39**	**0.02**	**-0.23***	**0.31**	**0.02**	**0.16**	**0.03**	**0.14***

*Significant difference within Canada or province.
Note: Because Newfoundland and Labrador, Prince Edward Island, and Saskatchewan did not oversample students by language, results for only English-language schools are available for these provinces.

Effects of exposure to teaching practices on science outcomes and attitudes toward science

Students' current and future engagement with science depends largely on their attitudes — in other words, whether they see science as important, useful, and enjoyable (OECD, 2008). Different teaching practices have an impact on the affective factors of learning, such as attitude, interest, and motivation (Savelsbergh et al., 2016).

Teacher-directed instruction is thought to be associated with passive learning, where students tend to use strategies like memorization, whereas enquiry-based teaching involves learning strategies like analysis and interpretation (Furtak et al., 2012). Teacher-directed and enquiry-based instruction practices each have a different impact on the extent of content taught, preparation for standardized testing, and development of collaboration and communication skills. Many studies have shown the effectiveness of teacher-directed instruction practices in a variety of school subjects (Bocquillon, Derobertmasure, & Demeuse, 2018; Hattie, 2012). The positive impact of enquiry-based teaching on science performance has been demonstrated in a large number of controlled experiments (Mostafa et al., 2018), but many meta-analyses have revealed contradictory results as to its effectiveness (Jiang & McComas, 2015).

This section will take a deeper look at the effects of exposure to the different teaching practices on attitudes toward science and science outcomes. In terms of attitudes, the analysis is limited to interest in science, which, in PISA 2015, consists of two indicators: interest in broad science topics and enjoyment of science. For Ainley and Ainley (2011), even though enjoyment and interest are two separate constructs in the literature, they serve complementary functions in the exploration of new subjects, and for acquiring new knowledge. With respect to science outcomes, it's important to remember that PISA assesses science literacy as "the ability to engage with science-related issues, and with the ideas of science, as a reflective citizen" (OECD, 2017, p. 22). Students must be able to explain phenomena scientifically using knowledge of scientific facts and concepts, evaluate and design scientific enquiry, and interpret data and evidence scientifically. Thus, science literacy is not strictly limited to content knowledge.

Interest in science

In 2015, PISA modelled an indicator of interest using five items related to specific science topics: the biosphere, motion and forces, energy and its transformation, the universe and its history, and how science can help us prevent disease. Students had to indicate their interest using a five-point Likert scale ranging from choice 1 (*Not interested*) to 4 (*Highly interested*) along with the option *"I don't know what this is."*

Enjoyment of science

PISA modelled an enjoyment indicator using five items, such as "I generally have fun when I am learning broad science topics." Students had to indicate their answer using a four-point Likert scale ranging from choice 1 (*Strongly disagree*) to 4 (*Strongly agree*).

Science outcomes

PISA science outcomes are expressed using a scale with an average of 500 points for OECD member countries and a standard deviation of 100. This average was established in 2006, the first year when science literacy was the major topic of assessment, and was re-established at 493 points in 2015.

Teaching practices and attitudes

Exposure to teacher-directed instruction practices and enquiry-based science teaching practices has a positive effect on interest in broad science topics and enjoyment of science, as measured in PISA 2015. Figures 5 and 6 show the variation of indices of attitude broken into quartiles for each type of practice in Canada.

In Canada, as in all provinces, increased exposure to teacher-directed instruction practices is associated with a higher index of enjoyment of science. The effect observed on interest toward science topics is weaker. Increased exposure to enquiry-based teaching practices is associated with an increase in the two indices of attitudes up to the second quartile at the pan-Canadian level, with a greater effect on enjoyment of science. The top quartile for the enquiry-based practices indicator is not, however, associated with higher indices of enjoyment and interest. Implementing effective enquiry-based practices requires time and resources. Among the challenges of implementing enquiry-based practices, implementation time is one of the most significant factors underscored by teachers (Hasni et al., 2018). The acquisition of a sufficient baseline of knowledge to place students in this type of instruction undoubtedly implies that, beyond a certain threshold, the frequency of these activities does not foster enough engagement. Thus, as Hofstein and Lunetta (2004) reveal, effective implementation of enquiry-based activities must be carefully structured so that students can work with both concepts and objects.

FIGURE 5 Index of enjoyment of science associated with quartiles for each teaching practice, PISA 2015

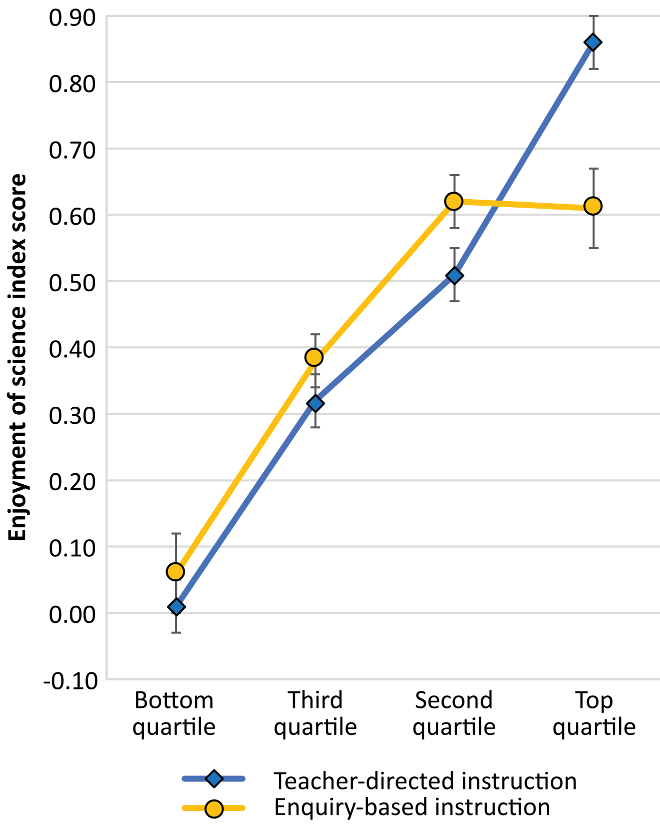
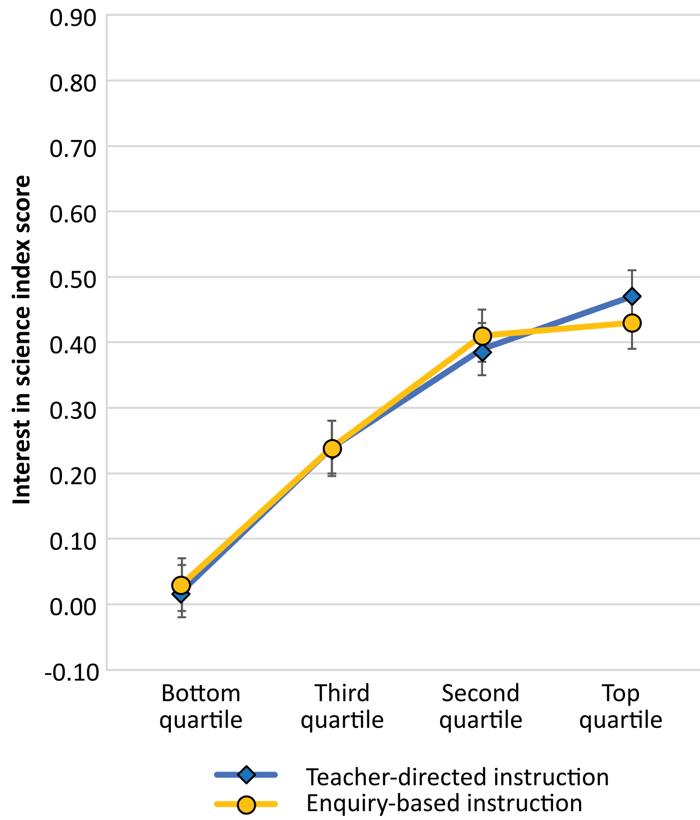


FIGURE 6 Index of interest in science associated with quartiles for each teaching practice, PISA 2015

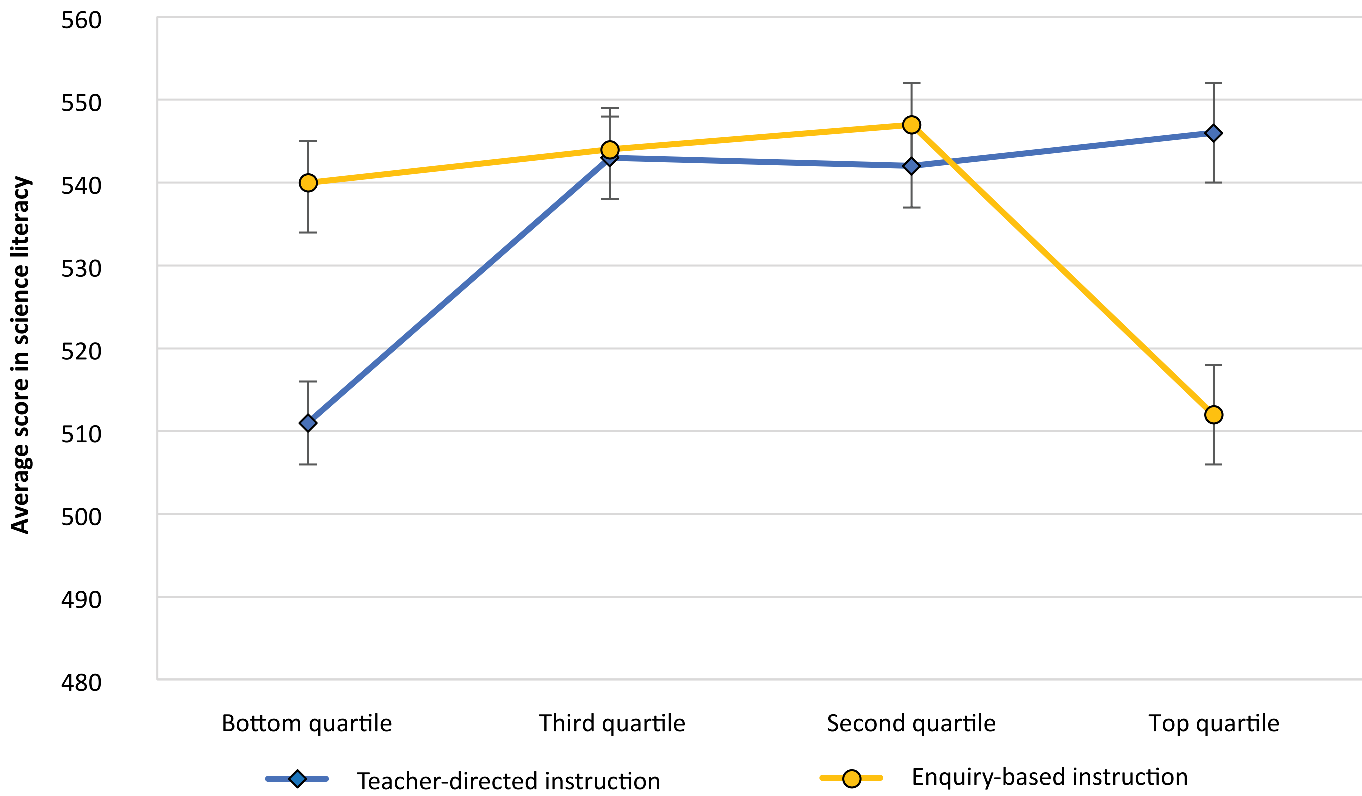


Teaching practices and science literacy assessment scores

As mentioned, students responded more positively (more frequent exposure) to the items for the index of teacher-directed instruction (0.37 in Canada, Figure 2) than to the items for the index of enquiry-based instruction (0.28 in Canada, Figure 4). A statistical analysis of associations between the indices and the PISA science scores reveals different effects. The index of teacher-directed instruction is positively associated with PISA science scores, while the association is negative in the case of enquiry-based instruction.

Considering the variations obtained per quartile in terms of attitudes, the same analysis applies here for science literacy assessment scores. Figure 7 shows PISA science scores associated with the different quartiles of teacher-directed instruction and enquiry-based teaching in Canada. Students in the bottom quartile of the teacher-directed instruction index, who reported that their teachers use teacher-directed instruction practices less frequently, attained lower science scores compared to their peers who reported more frequent use of such instructional methods in their classrooms. The analysis demonstrates that there is no statistically significant difference in science scores obtained in the subsequent quartiles, meaning that, beyond a certain threshold of exposure to teacher-directed instruction practices, few gains in scores can be expected. The opposite effect is seen in regard to the enquiry-based practices index. In this index, the top quartile clearly stands out because it has the lowest score, whereas the preceding quartiles had very minimal variations in science scores.

FIGURE 7 **Relationship between achievement in science literacy and teaching practice, by quartile**



Enquiry-based science teaching and teacher-directed instruction are not in opposition to each other; teachers can guide students — for example, by asking them to make some specific observations or requiring explanations about a phenomenon. Depending on the degree of open-endedness of activities (students' self-sufficiency) and the level of intervention by the teacher, differences can be seen between more or less advanced enquiries, with a greater or lesser effect on performance and on attitudes toward science (Jiang & McComas, 2015). Some studies have also empirically demonstrated that students who benefit from a mix of teacher-directed and enquiry-based approaches achieve better science scores (Blanchard, Southerland, Osborne, Sampson, Annetta, & Granger, 2010; Chen, Bae, Battista, Qin, Chen, Evans, & Menon, 2018).

Implications

Positive attitudes toward science can be fostered and maintained through a learning environment that presents novel activities and stimulates students' engagement with their learning, using a variety of teaching strategies to reach a greater number of learner profiles.

Teaching effectiveness relies on a combination of these factors rather than one factor in particular. For example, students do not readily make connections between multiple representations on their own during science activities and often hold disparate explanations for the same phenomena presented to them in the laboratory and in the classroom (O'Grady-Morris, 2008). Thus, minimally guided instruction, such as more open science enquiry, can be less effective and less efficient than instructional processes that guide student learning, because of the need to help the student make explicit connections between their observations and the abstract models used to explain scientific principles. Often teachers assume that students have made implicit connections between lesson content and their prior knowledge as they work through the experimental process, but the development of conceptual knowledge is also informed by strongly held and persistent misconceptions that result from the overgeneralization of scientific theory (O'Grady-Morris, 2008; O'Grady-Morris & Nocente, 2009). Therefore, better science outcomes cannot be achieved by only using research- and enquiry-based science teaching. Rather, these practices need to be combined with a supportive classroom climate and clear, well-structured classroom management. From this perspective, direct instruction and enquiry-based science teaching should not be seen as conflicting practices. According to Hasni et al. (2018), one of the major challenges in science education is to progressively lead students to take charge of their own enquiry activities. Scaffolding strategies (like questioning, reformulating, encouraging debate or reflection, and confrontation of statements) can be used, in this context, to support the acquisition of concepts and maintain a level of interest and enjoyment.

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