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RESEARCH ARTICLE

Comparative Analysis of PISA 2018 Science Achievement of High and Low Performers in Korea, Canada, and Taiwan

Shinyoung Lee[1],Hyunjung Kim[2]*

[1]Institute for Curriculum and Evaluation

[2]Kongju National University

*Corresponding Author: chem95@kongju.ac.kr

ABSTRACT

This study identified the strengths and weaknesses of Korean high and low performers in science, comparing their performance with Canadian and Taiwanese students. Using raw data from the 2018 Programme for International Student Assessment (PISA), correct answer rates were analyzed for the *Competency* and *Knowledge* dimensions within the PISA framework. Additionally, correct answer rates for each item were examined across high and low performers in the three countries. The findings are as follows. In Competence dimension, both Korean high and low performers showed a weaker evaluation and design of scientific inquiry and a stronger scientific interpretation of data and evidence compared to the analyzed countries. In Knowledge dimension, Korean high performers and students as a whole showed stronger procedural knowledge, biological system, and Earth and space system content knowledge, and epistemic knowledge. Item characteristics with high performers' lowest correct answer rate and low performers' highest correct answer rate by analyzed country were as follows. Korean high performers showed difficulty in item types with more than one correct answer and items that required epistemic knowledge to answer the question. low performers showed difficulty solving familiar items with frequently encountered problem situations and had difficulty with items related to the ecosystem.

Key words : PISA 2018, science domain, high performers, low performers, Canada, Taiwan

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Introduction

In Korea, the decline in scientific interest and competitiveness among primary and secondary school students has been worsening. Continuously decreasing interest in pursuing scientific careers has led to lack of individuals' development of basic scientific competencies and skills to meet societal demands (MSI, 2021). Because society faces increased uncertainty due to, for instance, COVID-19, climate change, digital transformation, and low birth rates, future societies will require—rather than those who simply memorize facts—individuals who can solve problems across various situations with minimal knowledge, information, and technology.

In response to growing uncertainty and the rapidly changing future environment, Korea is making significant efforts to cultivate scientific and technological talent to overcome crises and to transition to a leading economy. Over the next decade, however, a significant decrease in the influx of new personnel into science and technology fields is projected, thus widening the gap between supply and demand. This is expected to exacerbate mid- to long-term labor supply issues in these sectors, potentially leading to a talent shortage crisis (MSI, 2021).

In the future, the ideal individual will not receive knowledge passively but learn essential knowledge as a foundation for creative thinking, inquiry skills, and problem-solving abilities. This perspective has led to a focus on students' competencies. The Organisation for Economic Co-operation and Development (OECD) has been at the forefront of this movement, beginning with the Definition and Selection of Competencies (DeSeCo) project in 1997 and continuing with the Education 2030 project in 2015. These initiatives aim to present an educational blueprint suitable for changing times and to define the competencies students need to prepare for future societies (OECD, 2005; 2018b).

Additionally, the Programme for International Student Assessment (PISA) measures whether students possess the knowledge and skills necessary to be competent citizens in future societies (OECD, 2019a). PISA began in 2000, primarily among OECD countries and has completed eight cycles as of 2022. It targets 15-year-old students who have completed compulsory education and assesses cognitive domains such as reading, mathematics, and science. Alongside these assessments, PISA conducts surveys of students, schools, parents, and teachers to research various educational context variables that might influence cognitive achievement (OECD, 2019b). Through PISA, participating countries compare national and trend-based achievement results, enabling them to evaluate their students' competencies and review their educational policies and systems (Breakspear, 2012).

PISA results are analyzed by comparing countries, domains, trends, and achievement levels. A key analytic indicator is the ratio and mean difference between high and low performers (OECD, 2019b). Over the years, major PISA-participating countries, for example, Australia, Canada, the United Kingdom, and the United States, have analyzed high and low performers' means and ratios. These analyses identify and interpret educational disparities in each country according to its specific characteristics (NCES, 2019; O'Grady et al., 2019; Sizmur et al., 2019; Thomson et al., 2019).

Korea has also sustained its interest in high and low performers across different domains as indicated by PISA results. Seo (2011) used released items from PISA 2006 in the science domain to assess the scientific achievement of first-year high school students in the top 10% and also to examine gender differences in affective domains, finding no significant differences between males and females. Kim et al. (2013) categorized PISA 2009 science achievement into high, medium, and low performers, analyzing reading attitudes and methods' influence on scientific achievement by high performers compared to middle and low performers, confirming that reading attitudes and methods affected achievement across all groups.

Ku and Koo (2018) utilized PISA 2015 science results to analyze characteristics of educational context variables and their impact on achievement across different achievement levels, revealing that teacher support and tailored instructional methods effectively improved low performers' affective traits. Kim et al. (2020) investigated response time and time to first action of students classified as below basic proficiency (level 1 or below) in the PISA 2018 mathematics domain. They found that Korean students had shorter times compared to those from China, Japan, Taiwan, and the OECD average, indicating difficulties in solving problems in a computer-based assessment environment.

Lee and Kim (2021) analyzed educational context variables and their influences on Korean high, medium, and low performers in the PISA 2018 science domain, providing educational implications for students at different achievement levels. Kim (2021) compared achievement characteristics in the PISA 2018 science domain by analyzing ratios of achievement levels and correct response rates for the assessment framework's subcategories among the top five countries. The study found that the proportion of top-performing male students remained higher than that of female students, and the correct response rates for items related to personal context, design, and evaluation of scientific inquiry, epistemic knowledge, and higher-order cognitive demands had improved compared to PISA 2015.

However, no studies have analyzed achievement levels' characteristics by examining high and low performers' correct response rates in the PISA 2018 science domain and derived educational implications through international comparisons.

Since Korea began participating in PISA, it has consistently maintained a position among the top-performing countries. Since PISA 2015, however, the proportion of low performers has shown significant increase and remained steady (Cho et al., 2019). Therefore, identifying the characteristics of both high and low performers is essential, as is implementing tailored educational interventions based on these characteristics. Therefore, this study investigates higherand low performers' achievement characteristics through comparisons with other countries.

In the PISA 2022 science domain, South Korea (528) exhibited no statistically significant difference in average scores compared to Taiwan (537), Estonia (526), and Hong Kong (China) (520), despite actual score differences ranging from 2 to 11 points (OECD, 2023). In contrast, the PISA 2018 science assessment revealed that South Korea (519) had statistically similar average scores to Canada (518), Taiwan (516), and Hong Kong (China) (517), with actual score differences within 3 points (OECD, 2019b). Therefore, the PISA 2018 results are considered more appropriate for meaningful comparisons of high and low performers' achievement characteristics, as the smaller differences in average scores among countries with similar rankings provide clearer insights compared to those observed in PISA 2022. Additionally, it is posited that the varied responses to the COVID-19 pandemic among countries may have influenced science achievement in PISA 2022, further justifying the use of PISA 2018 data. As Hong Kong (China) is a city-state, it was excluded from the comparison, given the regional distribution, with Taiwan included as a comparable nation.

Because Canada and Taiwan's PISA 2018 science domain averages and rankings resemble those of Korea, those two countries were selected for comparison.

Canada has participated in PISA since the first cycle and, among Western countries, has consistently maintained high performers. As a federal country of multiple provinces, Canada allows each province to operate its education curriculum independently. For instance, British Columbia, which shows results similar to the overall Canadian average, implements a competency-based curriculum to ensure that students can successfully adapt to future societies (Kwon et al., 2018). Similarly, Taiwan has been a consistent top performer in the Asian region since its first participation in PISA. Taiwan operates a 6-3-3 education system, similar to Korea's and implements a competency-based curriculum designed to help students become lifelong learners based on core literacy (Cai, 2020). These two countries not only showed PISA 2018 science achievement results similar to Korea's but also apply the competency-based curricula that PISA advocates.

This study aims to identify Korean high and low performers' strengths and weaknesses in the science domain by comparing them with those of Canadian and Taiwanese students. Through this comparison, the study seeks to propose directions for science education tailored to the needs of Korean high and low performers.

The specific research questions are as follows.

1. What are the characteristics of high and low performers in the three countries in terms of *Competency* and *Knowledge* Dimensions?

2. What are the characteristics of correct answer rates of high and low performers in the three countries?

Materials and Methods

Materials

The analysis focused on raw data from three countries—Korea, Canada, and Taiwan—that exhibited similar achievements in the PISA 2018 science domain. Table 1 compares Korea's performance with the other two countries over the past four PISA cycles (2009–2018).

Table 1. Korea, Canada, and Taiwan's PISA science domain scores (2009–2018)

Countries	PISA 2009		PISA 2012		PISA 2015		PISA 2018	
	Mean score (SD)	Rank	Mean score (SD)	Rank	Mean score (SD)	Rank	Mean score (SD)	Rank
Korea	538 (3.4)	4~7	538 (3.7)	5~8	516 (3.1)	9~14	519 (2.8)	6~10
C anada	529 (1.6)	7~10	525 (1.9)	8~14	528 (2.1)	5~9	518 (2.2)	6~10
T aiwan	520 (2.6)	11~15	523 (2.3)	9~17	532 (2.7)	2~7	516 (2.9)	6~11

* SD : Standard Deviation

The three countries' student sample sizes were 6,650 from Korea, 22,653 from Canada, and 7,243 from Taiwan (OECD, 2018a), with participating students mostly in the 10th grade (OECD, 2019b). The OECD PISA headquarters first conducts school sampling and then manages the full sampling process. In Korea, stratified proportional sampling is conducted based on the entire school system's size, considering such factors as school type (middle, high, other various schools), program type (general, vocational), degree of urbanization (metropolitan, small/medium cities, rural areas), and school gender type (boys' school, girls' school, co-educational). Then from selected schools, student sampling is conducted randomly (Cho et al., 2019). In Canada, sampling is based on such factors as province, language, school size, degree of urbanization, source of school funding, and the International Standard Classification of Education. In Taiwan, such criteria as school type, source of funding, location, region, school gender composition, and local government jurisdiction are used (OECD, 2019b).

Data Analysis

Since the number of sampled students varies by country, PISA international headquarters establishes a weight variable and analyzes data based on a standard of 5,000 students (OECD, 2019b). This study followed that method of analysis. Classification of high and low performers also followed the international headquarters' standards. In the PISA 2018 science domain, achievement levels ranged from 1 to 6. Top student performers correspond to levels 5 and 6, while low performers fall below level 2 (OECD, 2019b).

To analyze students' achievement results in detail, the students were divided into groups based on their achievement levels; then the group proportions of high and low performers were compared over the last four cycles. Additionally, to analyze groups' specific achievement characteristics, correct answer rates were analyzed based on subcategories of Competency and Knowledge dimensions of the science domain assessment, which comprises four dimensions: *Context*, *Competency*, *Knowledge*, and *Cognitive demand*. *Context* refers to an item's situation, classified as *personal*, *local/national*, and *global* depending on its proximity to the individual. *Competency* refers to item elements constituting scientific literacy categorized into *explaining phenomena scientifically*, *evaluating and designing scientific inquiry*, and *interpreting data and evidence scientifically*. *Knowledge* encompasses varied science-related comprehension needed to demonstrate competencies, including *content knowledge* (*physical systems*, *living systems*, *Earth and space systems*), *epistemic knowledge*, and *procedural knowledge*. *Cognitive demand* refers to the depth of thinking required to solve a problem (OECD, 2019a). In the problem-solving process, *Competency* and *Knowledge* are directly required of students and are deemed to reflect students' characteristics at differing achievement levels. Therefore, comparison of students' correct answer rates focused on these two dimensions. Additionally, to identify achievement-level groups' characteristics exhibited during problem-solving, comparative analysis of item correct answer rates by achievement-level group was conducted. Because PISA uses trend items across cycles to track student achievement characteristics continuously and these items are not disclosed (OECD, 2019a), this study identified student achievement characteristics based on analysis of correct item answer rates.

Results

Characteristics of *Competency* and *Knowledge* Dimensions in High and Low Performers

In the PISA 2018 science domain, the proportion of high performers for the three countries was 11 % – 12 % (OECD average: 7 %), and of low performers 13 % – 15 % (OECD average: 22 %), indicating similar distributions (OECD, 2019b). The high performers are considered to be the future leaders of science and technology in each country, and the proportion of students with high performers indicates the direction of science education and gifted education in each country, while the proportion of students with low performers is used as a key figure to identify underachiever of basic education in each country.

In Korea, the proportion of high performers has remained relatively stable, while that of low performers increased significantly in PISA 2015 and has remained elevated. Canada also showed stability in the high performers' proportion, but that of low performers has been rising since PISA 2009. In PISA 2015, Taiwan experienced a significant increase in high performers' proportion, which in PISA 2018 declined to a level similar to Korea's. Also in Taiwan, the low performers' proportion has been increasing since PISA 2012, with a notable increase in 2018.

To understand high and low performers' characteristics in the science domain, we compared correct answer rates in the PISA 2018 *Competency* and *Knowledge* dimensions. As defined by PISA, Competency refers to social and epistemic practices commonly used in science. As noted above, these are categorized into *explaining phenomena scientifically*, *evaluating and designing scientific inquiry*, and *interpreting data and evidence scientifically* (OECD, 2019a). Table 2 displays average correct answer rates and differences between the three countries' high performers and low performers across the *Competency* dimension's subcategories.

Table 2. Differences in the three countries' high and low performers in the *Competency* dimension

Sub-categories (No. of items)	Levels	Correct answer rates (%)			Differences between countries (%p)	
		Korea	Canada	Taiwan	Korea - Canada	Korea - Taiwan
Explaining phenomena scientifically (47)	Higher	81.73	80.66	82.86	1.07	−1.12
	Lower	25.60	31.86	26.63	−6.26	−1.03
	All	55.02	55.65	55.47	−0.63	−0.45
Evaluating and designing scientific inquiry (29)	Higher	80.60	81.53	79.72	−0.93	0.88
					−4.22	2.37
				18.91		
			25.50			
	Lower	21.28				
					−2.39	1.09
				50.00		
			53.48			
	All	51.09				
					2.55	2.92
				88.11		
Interpreting data and evidence scientifically (36)	Higher	91.03	88.48			
	Lower	26.48	25.67	23.49	0.81	2.99
	All	61.87	59.79	58.84	2.08	3.03

In all three countries, average correct answer rates were the highest in interpreting data and evidence scientifically, followed by *explaining phenomena scientifically*, and then by *evaluating and designing scientific inquiry*. Korea had the highest correct answer rate in *interpreting data and evidence scientifically*, while Canada excelled in *evaluating and designing scientific inquiry* and *explaining phenomena scientifically.* For high performers, Taiwan led in explaining phenomena scientifically, Canada in *evaluating and designing scientific inquiry*, and Korea in *interpreting data and evidence scientifically*, differing from overall average trends. For low performers, Canada had the highest correct answer rate in *explaining phenomena scientifically* and *evaluating and designing scientific inquiry*, while Korea led in *interpreting data and evidence scientifically*.

In the PISA 2018 framework, knowledge was utilized to exhibit scientific literacy competencies, categorized into *content knowledge*, *procedural knowledge*, and *epistemic knowledge* (OECD, 2019a). Table 3 displays average correct answer rates and differences between the three countries' high and low performers across the *Knowledge* dimension's subcategories.

Table 3. Differences in the three countries' high and low performers in the *knowledge* dimension

Sub-categories (No. of items)		Levels	Correct answer rates (%)			Differences between countries (%p)	
			Korea	Canada	Taiwan	Korea - Canada	Korea - Taiwan
Content knowledge (46)	Physical systems (17)	Higher	85.56	83.59	85.26	1.97	0.30
		Lower	33.70	43.61	34.15	-9.91	-0.45
		All	60.16	62.49	59.78	-2.33	0.38
	Living systems (17)	Higher	79.26	81.32	83.84	-2.06	-4.58
		Lower	26.95	23.53	29.19	3.42	-2.24
		All	54.55	52.00	58.56	2.55	-4.01
	Earth and space systems (13)	Higher	78.08	77.61	80.75	0.47	-2.67
		Lower	24.28	28.80	23.17	-4.52	1.11
		All	55.62	54.81	55.65	0.80	-0.03
Procedural knowledge (47)		Higher	89.68	87.54	87.72	2.14	1.96
		Lower	25.85	27.05	22.87	-1.20	2.98
		All	59.98	58.97	57.78	1.01	2.20
Epistemic knowledge (18)		Higher	75.21	76.66	72.04	-1.45	3.17
		Lower	12.89	18.06	12.21	-5.17	0.68
		All	42.49	45.75	41.13	-3.26	1.36

In content knowledge, which includes *physical systems*, *living systems*, and E*arth and space systems*. Canada had the highest correct answer rate in *physical systems*, while Taiwan excelled in living systems and *Earth and space systems*. For high performers, Korea had the highest correct answer rates in *physical systems*, and Taiwan led in l*iving systems* and *Earth and space systems*. For low performers, Canada had a higher correct answer rate in *physical systems* and *Earth and space systems* compared to the other two countries, while Taiwan excelled in *living systems*. Generally, Taiwan's high performers exhibited a higher correct answer rate in *content knowledge*.

In *procedural knowledge*, Korea had the highest correct answer rate overall and within the high performers. In *epistemic knowledge*, Canada had the highest correct answer rates across all groups and overall.

Characteristics of Items' Correct Answer Rates in High and Low Performers

To analyze the achievement characteristics of Korea's high performers, we examined several items' correct answer rates. In all analyzed countries, items with the highest correct answer rates among high performers were rated close to or at 100 %, showing negligible differences among countries. Similarly, items with the lowest correct answer rates among low performers were below 3 %, nearly zero, making meaningful educational implications challenging through cross-country comparisons. Therefore, we analyzed the items with the lowest correct answer rates for high performers and the highest correct answer rates for low performers in each country to better understand the strengths and weaknesses of Korean students in problem-solving.

Table 4 shows the five items with the lowest correct answer rates for high performers in the three countries.

Table 4. The top 5 and bottom 5 Items by correct answer rates for high performers in the three countries

Items	Korea		Canada		Taiwan	
	Unit name (item code)	Correct answer rates (%)	Unit name (item code)	Correct answer rates (%)	Unit name (item code)	Correct answer rates (%)
Top 5	Nanop articles (CS 646Q01S)	100.00	Nanoparticles (CS646Q01S)	100.00	Nanoparticles (CS646Q01S)	100.00
	Invasive species (CS657Q01S)	100.00	Birds and caterpillars (CS607Q01S)	100.00	Birds and caterpillars (CS607Q01S)	100.00
	Comparing Light Bulbs (CS643Q01S)	100.00	Comparing Light Bulbs (CS643Q01S)	99.80	Comparing Light Bulbs (CS643Q01S)	100.00
	Spoons (CS256Q01S)	100.00	Elephants and Acacia Trees (CS603Q01S)	99.69	Elephants and Acacia Trees (CS603Q01S, Q03S)	100.00
	Urban heat island effect (CS602Q04S)	100.00	Oil Spilis (CS638Q02S)	99.19	Urban heat island effect (CS602Q01S)/ Fish Conservation (CS635Q02S)	100.00
Bottom 5	Extinction of the dinosaurs (CS527Q01S)	31.30	Tsunami (CS615Q05S)	36.07	Extinction of the dinosaurs (CS527Q01S)	27.43
	Urban heat island effect (CS602Q02S)	38.17	Wild oat grass (DS408Q03C)	43.24	Comparing Light Bulbs (DS643Q05C)	33.91
	Wild oat grass (CS408Q04S)	41.15	Vaccination (CS634Q04S)	45.79	Invasive species (DS657Q04C)	37.99
	Vaccination (DS634Q05C)	45.43	Extinction of the dinosaurs CS527Q01S)	46.50	Wild oat grass (DS408Q03C)	43.54
	Penguin island (DS 425Q04C)	47.02	Ammonoids (CS608Q01S)	53.23	Vaccination (CS634Q04S)	44.92

Examining the top 5 and bottom 5 items by correct answer rates for high performers in the three countries reveals differences in correct answer rates among the countries for the bottom 5 items. However, the top 5 items were similar across the three countries, with correct answer rates exceeding 99% and minimal differences in correct answer rates among the countries.

To identify areas where high performers in Korea may face relatively greater difficulties in solving items compared to students in other countries, we analyzed the bottom 5 items with differing correct answer rates among low performers in the three countries.

Items with the lowest correct answer rates did not completely overlap among countries. However, one common item was the first sub-item on Extinction of the dinosaurs, a complex multiple-choice question requiring students to read about dinosaur extinction and then answer questions based on the reading. Korea's high performers showed the second lowest correct answer rates on sub-items on *Urban heat island effect* and *Penguin island*, which did not appear among the lowest five items in Canada and Taiwan. Different sub-items of *Wild oat grass* and *Vaccination* were belong to each countries' five lowest-scoring items. Among these, the sub-items on *Extinction of the dinosaurs* and *Penguin island* were the ones with the lowest correct answer rates among Korean students. The overall correct answer rate for the sub-item on *Extinction of the dinosaur* was 11.43 %, and the overall correct answer rate for the sub-item on *Penguin island* was 31.82 % (Kim, 2021).

Table 5 compares the answer rates of Canada's and Taiwan's high performers for the five questions with the lowest correct answer rates among Korea's high performers.

Table 5. Correct answer rates for the bottom 5 Items across three countries based on Korea's high performers

	Unit name (item code)	Correct answer rate (%)			Differences between countries (%p)	
		Korea	Canada	Taiwan	Korea - Canada	Korea - Taiwan
1	Extinction of the dinosaurs (CS527Q01S)	31.30	46.50	27.43	-15.20	3.87
2	Urban heat island effect (CS602Q02S)	38.17	53.54	51.55	-15.37	-13.38
3	Wild oat grass (CS408Q04S)	41.15	77.39	77.00	-36.23	-35.84
4	Vaccination (DS634Q05C)	45.43	56.61	48.53	-11.18	-3.10
5	Penguin island (DS425Q04C)	47.02	77.23	60.30	-30.21	-13.28

First, for the item with the lowest correct answer rate among high performers, the sub-item on *Extinction of the dinosaurs*, Korea's correct answer rate was more than 15 percentage points lower than that of Canada. The sub-item on *Urban heat island effect* had correct answer rates approximately 13–15 percentage points lower in Korea than in both Canada and Taiwan. For the sub-item on *Wild oat grass*, Korea's high performers scored about 36 percentage points lower than those in Canada and Taiwan. The sub-item on *Vaccination* showed that Korea's high performers had a correct answer rate approximately 11 percentage points lower than Canada's and about 3 percentage points lower than Taiwan's. Lastly, for the sub-item on Penguin Island, Korea's high performers had a correct answer rate 30 percentage points lower than Canada's and 13 lower than Taiwan's.

These items showed a significant difference in correct answer rates between Korea's high performers and those of Canada and Taiwan, indicating that on certain types of questions, Korea's high performers struggle more than their counterparts. Characteristics of items that Korea's high performers found relatively difficult are summarized as follows:

A complex multiple-choice question, the sub-item on *Extinction of the dinosaurs* asks about relatively unfamiliar epistemic knowledge. The item's text is lengthy, and the options include "both," meaning there may not be a single correct answer.

The sub-item of *Urban heat island effect* involves reading the given material and selecting an explanation for the phenomenon. This item also includes options that may have "one or more" correct answers; that is, the item may not have a single correct answer.

The sub-item of *Wild oat grass* is a complex multiple-choice question requiring all three selections to be correct for the item to be rated correct. Moreover, the Wild oat grass item's context is not commonly encountered in Korea's science classes or in daily life, so such an unfamiliar context proved challenging even to Korea's high performers.

The sub-item on *Vaccination* pertains to the competency of evaluating and designing scientific inquiry, for which Korea's correct answer rate has been the lowest since PISA 2015 (Kim, 2021). Students might find it difficult to understand the item's specific terms, leading to confusion between these terms and those used in everyday language.

The sub-item on Penguin Island requires epistemic knowledge, requiring students to judge whether the provided data supports the given argument and to assess the data's reliability. This type of question is unfamiliar to Korean students.

To analyze problem-solving characteristics among Korean low performers, we examined items with the highest correct answer rates for each country's low performers (Table 6).

Table 6. The Top 5 and Bottom 5 Items by correct answer rates for low performers in the three countries

Items	Korea		Canada		Taiwan	
	Unit name (item code)	Correct answer rates (%)	Unit name (item code)	Correct answer rates (%)	Unit name (item code)	Correct answer rates (%)
Top 5	Spoons (CS256Q01S)	84.99	Birds and caterpillars (CS607Q01S)	77.02	Spoons (CS256Q01S)	85.49
	Invasive species (CS657Q01S)	76.59	Spoons (CS256Q01S)	76.18	Invasive species (CS657Q01S)	80.16
	Urban heat island effect (CS602Q01S)	75.72	Brain-controlled robotics (CS610Q02S)	67.53	Birds and caterpillars (CS607Q01S)	77.26
	Birds and caterpillars (CS607Q01S)	70.16	Tornadoes (CS620Q01S)	64.57	Car tyres (CS627Q03S)	61.88
	Tsunami (CS615Q01S)	68.55	Development and disaster (DS514Q02C)	61.89	Urban heat island effect (CS602Q01S)	60.13
Bottom 5	Vaccination (CS634Q01S))	0.00	Save the Fish (DS635Q05C)	0.00	Nanoparticles (DS646Q05C)	0.00
	Comparing Light Bulbs (DS643Q03C)	0.00	Vaccination and Spreading of Disease (CS634Q01S)	1.34	Comparing Light Bulbs (CS643Q04S)	0.00
	Habitable Zone (DS648Q01C)	0.00	Nanoparticles (DS646Q05C)	2.20	Comparing Light Bulbs (DS643Q05C)	0.00
	Vaccination (DS634Q03C)	0.04	Extinction of the dinosaurs(CS527Q01S)	2.36	Save the Fish (DS635Q05C)	0.27
	Save the Fish (DS635Q05C)	0.44	Comparing Light Bulbs (DS643Q03C)	2.37	Vaccination (DS634Q05C)	0.91

Examining the top 5 and bottom 5 items by correct answer rates for low performers in the three countries reveals differences in correct answer rates among the countries for the top 5 items. However, for the bottom 5 items, correct answer rates were below 4%, with minimal differences in responses across the three countries

Examining the top 5 and bottom 5 items by correct answer rates for low performers in the science domain reveals some differences in correct answer rates among the three countries for the top 5 items. However, for the bottom 5 items, correct answer rates were below 4%, with minimal differences in responses across the three countries. To identify areas where low performers in Korea may face relatively greater difficulties in solving items compared to students in other countries, we analyzed the top 5 items with differing correct answer rates among low performers in the three countries.

Across the three countries, items with the highest correct answer rates were not identical, but two—*Spoons* (sub-item 1) and *Birds and caterpillars* (sub-item 1)—were commonly among the top five for all three countries. Table 7 compares the answer rates of Canada's and Taiwan's low performers for the five questions with the highest correct answer rates among Korea’s low performers.

Table 7. Correct answer rates for the top 5 Items across three countries based on Korea's low performers

	Unit name (item code)	Correct answer rate (%)			Differences between countries (%p)	
		Korea	Canada	Taiwan	Korea - Canada	Korea - Taiwan
1	Spoons (CS256Q01S)	84.99	76.18	85.49	8.82	-0.49
2	Invasive species (CS657Q01S)	76.59	59.87	80.16	16.71	-3.58
3	Urban heat island effect (CS602Q01S)	75.72	57.00	60.13	18.72	15.58
4	Birds and caterpillars (CS607Q01S)	70.16	77.02	77.26	-6.86	-7.10
5	Tsunami (CS615Q01S)	68.55	58.60	55.87	9.95	12.68

The item with the highest correct answer rate for Korea's low performers was the sub-item on Spoons, which also had the highest overall correct answer rate in Korea. The correct answer rate for Korea's low performers was approximately 9 percentage points higher than Canada's. For the sub-item on Invasive species, Korea's low performers had a correct answer rate approximately 17 percentage points higher than Canada's, but about 4 percentage points lower than Taiwan's. Sub-items on Urban heat island effect and Tsunami also showed higher correct answer rates for Korea's low performers compared to Canada and Taiwan's, with the *Urban heat island* effect being about 16 percentage points higher and *Tsunami* about 10 percentage points higher.

However, the sub-item on *Birds and caterpillars* had a correct answer rate for Korea's low performers that was about 7 percentage points lower than those of Canada and Taiwan, indicating that Korean students in this group struggled more with this item than did their peers in the other two countries.

Overall, this suggests that low performers in Korea find certain types of questions easier or harder compared to their counterparts in other countries. First, the items that Korea's low performers found easier than Canada and Taiwan's low performers include sub-items from *Urban heat island effect* and *Tsunami*. The sub-item on *Urban heat island effect* contains content frequently covered by the Korean media, making it familiar to students who could select the correct answer even without reading the provided materials. By simply interpreting the given graphs, students could solve the problem easily. The sub-item on Tsunami is a simulation question related to tsunami occurrences. Although students need to select and manipulate variables to perform the simulation, the concept of tsunami is also familiar to Korean students due to media coverage and films. The simplicity of the simulation process allows intuitive problem-solving.

Conversely, the sub-item on *Birds and caterpillars* posed a greater challenge for Korea's low performers than for those in Canada and Taiwan. This question asked students to identify ecosystem components from a provided image. Despite being an easy question with an overall correct answer rate of over 90 % in Korea, the correct answer rate for Korea's low performers was about 7 percentage points lower than that of their counterparts in Canada and Taiwan. This discrepancy is likely due to Korean students not recently encountering ecosystem-related knowledge in their curriculum content. Korean students who took PISA 2018 were taught under the 2009 revised curriculum, in which ecosystems' components are covered in the science curriculum for grades 5–6 and in the optional Life Science I course for high school grades 2–3.

Discussions

The PISA 2018 science results for Korea, Canada, and Taiwan had similar proportions of high and low performers. However, over the last four cycles, Canada had high performers exceeding 12 % in half the cycles, while Taiwan had instances in which the proportion exceeded 15 %. In contrast, Korea's proportion of high performers was from 10 % to 12 %, never exceeding 12 %. During the same four cycles top-performing countries showed the following PISA results: Singapore's top-performing students ranged from 19.9 % to 24.2 %, Japan's from 15.3 % to 18.2 %, and Finland's from 12.3 % to 18.7 % (Kim, 2021). To transition to a leading economy by cultivating excellent science and technology personnel, increasing the proportion of high performers is essential. Unfortunately, Korea's proportion of low performers rose significantly in PISA 2015 and remained at that level in 2018. Proportions of low performers in Singapore were 9.0 % to 9.6 %, in Japan 9.6 % to 11.1 %, in Estonia 8.87 %, and in Finland 11.5 % to 12.9 % (Kim, 2021)—contrasting significantly with Korea's proportion at 14.2 % to 14.4 %. To ensure students possess basic scientific literacy essential for life in future society, reviewing and strengthening basic academic skills are crucial actions.

Across the three analyzed countries, high and low performers' answer rates for solving PISA problems were compared in the Competency and Knowledge dimensions. First, in the Competency dimension, Korea showed higher answer rates in scientific interpretation of data and evidence for both high and low performers and for the overall answer rate, compared to Canada and Taiwan indicating Korea's strength in scientific interpretation of data.

For both high and low performers and for the overall answer rate, Canada had higher answer rates in the *Competency* dimension of *evaluation and design of scientific inquiry* and the *Knowledge* dimension of *epistemic knowledge*. This is attributed to Canada's inquiry-centered science curriculum; in British Columbia, for example, the teaching and learning model focuses on scientific competencies such as questioning and predicting, planning and conducting, processing and analyzing data and information, evaluating, applying and innovating, and communicating (Government of British Columbia, 2024). Science achievement standards include elements such as fair testing, identifying possible sources of error, suggesting improvements to inquiry methods, recognizing causes of error and uncertainty, identifying alternative explanations and conclusions, and evaluating one's methods and experimental conditions (Kim, 2021). This inquiry-based approach focusing on epistemic practices seems to contribute to the high answer rates in *evaluation and design of scientific inquiry*.

Taiwan's high performers had the highest answer rates in the competency of *scientific explanation of phenomena*. In the *Knowledge* dimension, high performers also showed high answer rates in the knowledge of physical systems, living systems, and Earth and space systems. The competency of *scientific explanation of phenomena* largely relies on content knowledge (OECD, 2019a), indicating that Taiwanese high performers well understand content knowledge, likely because the Chinese characters used in Taiwanese science textbooks encapsulate scientific terms' meaning, thereby aiding students' conceptual understanding (Kim & Kim, 2010). Notably, compared to Canada and Korea, Taiwan showed significantly higher answer rates in the living systems category for both high and low performers. This finding aligns with 2019 Trends in International Mathematics and Science Study (TIMSS) results, on which Taiwan outperformed Korea in biology and chemistry by 16 % and 43 % points, respectively, despite scoring lower in physics and Earth science (Sang et al., 2020). Compared to other Chinese-speaking regions like China, Hong Kong, and Macau, in Taiwan, the proportion of memorization of scientific factual and conceptual knowledge is higher in science curriculum (Wei & Ou, 2019).

Across countries, by comparing high performers' lower answer rates and low performers' higher answer rates and analyzing each item's characteristics, Korean students' performance characteristics can be summarized as follows.

Korean high performers struggled with multiple-choice items that could have more than one correct answer, for instance, "one or more" or "both." Korean examinations do not commonly include such items, so students are unfamiliar with them. Additionally, Korean high performers found it challenging to solve inquiry items that required epistemic knowledge, for example, exploring multiple possibilities, discussing topics, and examining the validity of conclusions drawn from data.

Korean low performers performed relatively well on items related to familiar topics from the science curriculum or everyday life and those answered by carefully reading provided information or performing simple tasks. However, their answer rates were lower on ecology-related items on which students from other countries performed well, perhaps because Korea's 2009, 2015, and 2022 revised curricula, did not cover ecology-related content in middle school. Given increasing interest in the global ecosystem, incorporating ecology-related content into the life sciences curriculum beyond elementary school may be necessary.

Conclusions & Implications

In this study, Canada and Taiwan, countries with PISA achievements similar to those of Korea in the 2018 PISA science domain, were selected for comparison to identify Korean high and low performers' strengths and weaknesses in the science domain.

First, Canada, with an average score similar to Korea's in the science domain, scored 2.39 percentage points higher in the competency of *evaluating and designing scientific inquiry.* This trend was similar in both high performers and low performers' correct response rates. In this competency, Korea's correct response rate was the lowest compared to such high-achieving countries as Singapore, Estonia, Japan, and Finland (Choi et al., 2021). Compared to Canada and Taiwan, both Korean high performers and low performers excelled in the competency of interpreting data and evidence scientifically, suggesting the Korean curriculum's strengths in fostering this competency. In contrast, compared to countries like Canada, the Korean curriculum is relatively lacking in the competency of *evaluating and designing scientific inquiry*. Kim (2021) similarly pointed this out.

Second, to enhance the competency of *evaluating and designing scientific inquiry* among Korea's high performers, education fostering inquiry competencies based on epistemic knowledge must be strengthened. Compared to Canada and Taiwan, high performers' correct response rate in this competency dropped significantly from PISA 2009 to PISA 2018 (–5.29 percentage points), indicating difficulties with *epistemic knowledge* questions, for example, identifying scientific questions, distinguishing them from non-scientific questions, proposing or evaluating methods to explore given questions, and explaining and evaluating various methods used to ensure data's reliability (OECD, 2019a). Given that Korea's high performers possessed superior conceptual knowledge and higher-order thinking skills compared to middle and low performers, strengthening science inquiry education that applies epistemic knowledge is essential for high performers. The high performers are likely to grow into STEM talents who will lead Korea's future industries. Considering Japan and Singapore, which have high rates of high performers (Kim, 2021), strengthened science education for high performers in Korea will help Korea establish itself as a science and technology powerhouse in the future society.

Third, in the *Knowledge* dimension, compared to Canada and Taiwan, Korea's correct response rate in *procedural knowledge* was relatively higher for both overall and high performers. In the *content knowledge* dimension, however, only Korea's high performers showed a higher correct response rate in *physical systems*, while Canada or Taiwan had higher correct response rates in *biological systems*, *Earth and space systems*, and *epistemic knowledge*. For Korea to lead future society, strategically fostering advanced industries—the driving force of its growth—and securing talent to drive innovation in advanced industries are crucial strategies (MOE, 2023). Therefore, analyzing why Korea lags behind Canada and Taiwan in all subcategories of *Knowledge* except *procedural knowledge* and why Korean high performers' correct response rate is lower in, for instance, *biological systems* is necessary. Additionally compared to Canada and Taiwan, Korea's low performers did not earn the highest correct response rate in any subcategory of Knowledge dimension. In fact, Canada had the highest correct response rate in all subcategories of *Knowledge* dimension except *biological systems*. In *physical systems*, the correct response rates of Korea and Canada's low performers showed about a 10 % difference and in epistemic knowledge about a 13 % difference, indicating an urgent need to address and enhance low performers' basic competencies.

Based on these research results, the following are recommended for science education for groups with high and low performers.

First, to cultivate excellent scientific talent, which is the driving force of national growth, understanding various student groups' characteristics and providing them with appropriate education are necessary actions. For high performers, gifted classes should be expanded for in-depth science education; regional science gifted education centers should be established to support R&E programs; and teacher support plans should be devised to foster free-inquiry teaching and learning capabilities.

Second, continuous support is needed to improve access to science inquiry education, so low performers can gain basic scientific literacy. Besides improving cognitive achievement, low performers can improve affective achievement, for instance, class participation, interest, and curiosity, through student-centered teaching and learning processes (Choi, Lee, & Kim, 2014). Because various applications and programs that enable real-time interaction have been introduced following COVID-19, encouraging students to participate in inquiry-based classes using these tools and also supporting students' individualized learning are necessary strategies.

Third, epistemic knowledge must be reviewed and consistently supplemented throughout the curriculum. TIMSS queries content knowledge based on the curriculum mainly, but PISA does not. Instead, due to its competency-based evaluation, PISA assesses students' actual cognitive achievement results (Rim, 2016). Although Korea's 2015 revised curriculum and the newly applied 2022 revised curriculum emphasize process and function that include epistemic practices along with the elective curriculum's common subjects, "Science Inquiry Experiment 1 and 2" directly present content related to epistemic knowledge; however epistemic knowledge is not explicitly presented in the common elementary and middle school curriculum. Therefore, the next curriculum should explicitly specify science and scientific inquiry, as in the "What is Science?" unit of the 2009 revised curriculum, and expand parts that can enhance students' understanding of science and scientists' activities.

Conflicts of Interest

The authors declared no conflicts of interest.

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Authors' Information

Lee, Shinyoung: Korea Institute for Curriculum and Evaluation, Research Fellow, First Author, https://orcid.org/0000-0002-2476-8546

Kim, Hyunjung: Kongju National University, Associate Professor, https://orcid.org/0000-0001-6223-9816