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Insights from coherence in students' scientific reasoning skills

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ABSTRACT

Improving scientific reasoning enables students to navigate the challenges of learning science. Teachers use Lawson's classroom test of scientific reasoning (LCTSR) to measure scientific reasoning. The LCTSR is a two-tiered assessment that uses content-based questions and explanation statements. Researchers have found that if a student answers a knowledge-based question correctly but selects an incorrect explanation statement, there may be an element of guessing or an established misconception. Misconceptions are beliefs that students hold that are not based on scientific evidence. The present study added a confidence variable to the LCTSR, which measures how confident students regarded their responses in both tiers. Selecting a correct response to a knowledge-based question while providing an incorrect explanation and having a high confidence rating indicates an established misconception. The confidence variable is, therefore, a measure of an established scientific misconception and is the basis of the present study. The present study analyzed the responses of 71 first-year university students enrolled in an introductory physics course. The LCTSR results indicate that students performed the best in the conservation reasoning dimension and the worst in the proportional reasoning dimension. In all scientific reasoning dimensions, more than half the students chose the incorrect explanation for each context question. Students' confidence responses surpassed their performance in three of the 14 LCTSR items. The low frequency of correct answers and the statistically significant correlation between LCTSR items and confidence suggest possible misconceptions in students' scientific reasoning skills.

1. Introduction

1.1. Rationale of the study

The rationale of the study was to establish if there is coherence in students' knowledge and scientific reasoning skills. If there is consistency in students' incorrect reasoning patterns, it would indicate stable misconceptions that needs to be addressed. Insights from the coherence or no coherence of students' scientific reasoning skills provides a unique way to look into student misconceptions, as students might apply scientifically incorrect knowledge consistently with confidence. The goal is the ability to measure and thereby exercise control over a latent factor such as misconceptions in science, that may be responsible for poor learning outcomes.

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1.2. Contemporary science education

1.2.1. The role of science

Science aims to increase our understanding of life and the world by constructing knowledge and developing reasoning skills. The role of science education is to develop scientific literacy by implementing the scientific method, which enables students to think, learn, find solutions, and make informed decisions based on a scientific framework that ultimately serves the best interests of society. Tracking the progress of these global education systems through international large-scale assessments (ISLAs) such as the Trends in Mathematics and Science Assessment (TIMSS) and the Programme for International Student Assessment (PISA) means that there is no place for education stakeholders and policymakers to hide, from poor results. The positive aspects of ILSAs are that they allow education systems to track their students' performance on the global stage and, secondly, to adopt the best practices of top-performing countries.

The historical trend of the TIMSS indicates that African countries such as South Africa, Botswana, Morocco, and Egypt, have consistently been placed at the bottom of the TIMSS rankings. The cognitive domain of the TIMSS science assessment framework indicates that 20% of the Grade 4 and 30% of the Grade 8 science assessments tests scientific reasoning [1]. The poor results in the science study indicate that there is a problem of scientific reasoning ability and stakeholders in science education systems must find ways of addressing this problem. The first step in addressing the problem is determining if the students in the science class have the cognitive ability to be there. More importantly, how can the situation be alleviated if they do not. One of the methods used to identify a student's scientific ability is an assessment of their scientific reasoning skills.

Scientific reasoning refers to the ability of students to construct new knowledge and learn science through observation, evaluation, interpretation, and theoretical explanation [2]. Scientific reasoning is discussed in the next section.

1.2.2. Scientific reasoning

Scientific reasoning is often described as the collection of cognitive abilities engaged in higher-order thinking. Skills related to scientific reasoning generally form part of school and university science curricula [3]. An application of scientific reasoning is identified in pedagogic environments that require students to learn the scientific method involved in performing experiments. A typical hypothetical-deductive school experiment may start with observing a phenomenon, identifying possible underlying variables, stating hypotheses, compiling experiments using control variables, analysing the results, formulating conclusions, and writing a report. Each of these processes involves thinking skills and reasoning abilities applied in the experiment's context.

As a skill, scientific reasoning is key to ensuring the effective learning of science. Although scientific reasoning plays a vital role in supporting critical thinking [4] and is an inherent characteristic of science [5], the problem is that students who reason consistently do not necessarily think and reason through a scientific framework [6]. Lemmer [6] showed that due to scientific misconceptions, students might confidently and consistently apply scientifically incorrect knowledge. In contrast, students that do not access scientific reasoning skills referred to as naïve students, display reasoning skills that are often context-dependent and do not apply the same processes to build new knowledge [7]. Naïve students tend to consider the situational context when solving problems and may consequently apply diverse methods to solve similar problems set in different contexts, called isomorphic problems [8]. Isomorphic problems are referred to as problems that can be solved using the same physics principles [9]. A measurement of scientific reasoning skills is required to distinguish between students who reason through consistent misconceptions and situational contexts with those that reason using scientific reasoning skills. An example of a scientific misconception is that the mass of an object depends on the shape and size of the object [10]. Students that demonstrate this misconception believe that if the size of an object is reduced, then it will have a smaller mass. The situational context reinforcing the misconception is that larger objects tend to have a larger mass. The first step to dispelling this misconception, is the identification of the misconception through assessment. The tools and instruments available to measure scientific reasoning skills are discussed in the next section.

1.2.3. Tools and instruments to measure reasoning skills

Measuring learners' scientific reasoning skills is important because it allows educators and researchers to understand how well students are able to apply scientific thinking to real-world problems and make sense of scientific information [11]. This understanding can then be used to improve science education by identifying areas where students are struggling and developing strategies to support their learning [12]. Additionally, measuring scientific reasoning skills can also be useful for assessing the effectiveness of different teaching methods and curriculum materials [13]. Overall, measuring scientific reasoning skills can help to ensure that students are developing the critical thinking and problem-solving skills that are necessary for success in science and in other areas of life [14].

Several tools and instruments have been developed to measure student's scientific reasoning skills, including Lawson's Classroom Test of Scientific Reasoning (LCTSR [15]), the Group Assessment of Logical Thinking Test (GALT [16]), the Test of Logical Thinking (TOLT [17]) and several variations and adaptations thereof [18–22]. Although the GALT and the TOLT have comparatively high reliability for internal consistency [23,24], the two-tier design of the LCTSR renders it the most popular instrument to assess scientific reasoning skills [3]. The following section provides a brief description of the LCTSR.

1.2.4. Lawson's classroom test of scientific reasoning (LCTSR)

Each question of the LCTSR assesses scientific reasoning in different contexts and may therefore be used as an indication of coherent scientific reasoning abilities outside a single experimental setting. The student's ability to transfer knowledge to new contexts indicates their scientific reasoning ability across multiple contexts [25]. Using a two-tier system of multiple-choice questions, the LCTSR measures the student's reasoning ability. The literature on scientific reasoning skills reviewed as part of the present study included the effect of age or grade level [26,27], gender [28], academic achievement [29], attitude [30], and culture of problem solving [31] on reasoning ability. The application of the LCTSR in the present case study is unique in that it explores the concept of scientific misconceptions concerning scientific reasoning skills. The addition of the confidence variable into the LCTSR establishes scientific misconceptions by exploring the correlation between correct responses to content-based statements, explanation statements, and confidence responses. Identifying scientific misconceptions associated with scientific reasoning ability provides an added assessment function that teachers may use to determine, address, and resolve problems that students experience when learning science. The theoretical framework discusses the six dimensions of scientific reasoning in terms of the specific LCTSR items and the implications of student understanding for each dimension.

The LCTSR has been used in studies that measured the difference of scientific reasoning ability. The theoretical framework of the present study is discussed in the next section.

1.3. Theoretical framework

The theoretical framework is presented before the literature review section to define and explain the concepts used in scientific reasoning. Lawson [15] used Piaget's theory of intellectual development and information processing as a framework for the LCTSR. The LCTSR measures the scientific reasoning skills to determine the extent of a student's cognitive understanding across six dimensions [32]. The six scientific reasoning dimensions of the LCTSR comprise conservation of mass and volume, proportional reasoning, control of variables, probability reasoning, correlational reasoning, and hypothetical-deductive reasoning, as indicated in Table 1. Table 1 also indicates the item number and the topic area of the LCTSR associated with each scientific reasoning dimension.

Each scientific reasoning dimension of the LCTSR (Table 1) is discussed in the following sections.

1.3.1. Conservation dimension

LCTSR Items 1 and 2 test for conservation of mass reasoning, and Items 3 and 4 test for conservation of volume reasoning [3]. On attaining an understanding of the conservation of mass, students realise that when a solid body is transformed (e.g., by a change in shape or division), its quantity of matter and its weight and volume remain unaffected. Therefore, a clay ball is immersed in a glass of water, will displace a specific volume of water, irrespective of its shape. The questions in LCTSR that involve the conservation of weight and displaced volume require logical operations associated with concrete reasoning from the students' experiences [33].

1.3.2. Proportional reasoning dimension

LCTSR Items 5 to 8 test for proportional reasoning [3]. These items include content based on pouring water between wide and narrow cylinders and predicting levels. In understanding proportional reasoning, students realise that proportional reasoning involves the comparison of multiplicative as opposed to additive relationships between rational numbers [34]. Proportional reasoning is a core mathematical concept used when solving problems involving quantitative proportional relationships [35]. Applications are found in various subjects, such as economy and science, as well as everyday life situations (e.g., when adjusting recipes for baking).

1.3.3. Control of variables dimension

LCTSR Items 9 to 14 test for control of variables reasoning [3]. Items 9 and 10 include content based on designing experiments to test the influence of the length of a string on the period of a pendulum. Items 11 to 14 include content based on using fruit flies in tubes to examine the influence of red/blue light and gravity on flies' responses. On achieving an understating of the control of variables, students realise that changing the independent variable may increase, decrease, or not affect the dependent variable.

1.3.4. Probability dimension

LCTSR Items 15 to 18 test for probability reasoning [3]. Items 15 to 18 include content based on predicting chances for withdrawing certain coloured wooden blocks from a sack. In understanding probability reasoning, students realise that probability is used in daily life to make decisions when the outcomes are uncertain. Students also realise that subjective probability may be used to make decisions

Table 1
Scientific reasoning dimensions, item numbers and topic areas of the LCTSR.

Dimension	Item number	Topic area
Conservation of weight	1, 2	The effect on mass by of changing the shape of two identical clay balls
Conservation of volume	3, 4	The effect on displaced volume by a glass marble of equal size and a heavier steel marble.
Proportional reasoning	5, 6, 7, 8	The effect on height by changing the width of measuring cylinders while keeping the volume constant.
Control of variables	9, 10	The effect of string length on the period of a pendulum by varying the mass of the pendulum.
	11, 12	The effect of red light and gravity on fruit flies.
	13, 14	The effect of blue light and gravity on fruit flies.
Probability	15, 16	The chance of picking red blocks from a bag of red and yellow identical blocks.
	17, 18	The chance of picking red round or blue round pieces of wood from a bag of red, blue and yellow round and square pieces of wood.
Correlational reasoning	19, 20	Predicting if there is a correlation between the mice size and tail colour from given pictorial data.
Hypothetical-deductive reasoning	21, 22	Design an experiment to investigate why waters rises in an inverted glass that covers a lit candle in a water bath.
	23, 24	Design an experiment to investigate why red blood cells shrink after adding salt water to the sample.

affecting the selection of multiple options, highlighting the role of probabilistic concepts in the decision-making process. Although the concept of probability is widely accepted as part of school mathematics curricula, students find it challenging to understand, and teachers find it difficult to teach [36].

1.3.5. *Correlation reasoning dimension*

LCTSR Items 19 and 20 test correlation reasoning [3]. Items 19 and 20 include content based on predicting whether a correlation exists between the size of the mice and the colour of their tails through presented data. In understanding correlation reasoning, students realise that, firstly, correlation reasoning relates to the ability to determine the covariation of variables within a sample [37]. Secondly, the covariation of continuous variables implies that if an independent variable is steadily increased, the dependent variable will increase or decrease similarly [38]. Thirdly, if a change in one variable does not give rise to a change in another variable, they are called non-variant variables. Fourthly, multiple variables may simultaneously influence an outcome. Fifthly, multivariable variance frameworks assume causal consistency; in other words, if the same conditions apply, similar causes will have the same effects [39].

1.3.6. *Hypothetical-deductive reasoning dimension*

LCTSR Items 21 to 24 test hypothetical-deductive reasoning [3]. Items 21 and 22 include content based on designing experiments to determine why the water rushed up into the glass after the lit candle went out. Items 23 and 24 include content based on designing experiments to determine why red blood cells become smaller after adding a few drops of salt water. Hypothetical-deductive reasoning is a skill based on arriving at a specific conclusion from a given premise. In understanding hypothetical-deductive reasoning, students realise that deductive reasoning is not dependent on facts but on the given premise [40]. A student displaying hypothetical-deductive reasoning skills realises that a conclusion must be proper if the premise is true [41].

The following section presents the literature reviewed on scientific reasoning, misconceptions in science, self-confidence, the correlation between LCTSR dimensions, and the LCTSR as a valid and reliable instrument for assessing students' scientific reasoning skills.

1.4. *Literature review*

1.4.1. *Literature on scientific reasoning*

The labels and descriptions of scientific reasoning have transitioned over time. Scientific reasoning skills have been described as formal reasoning skills [15], critical thinking skills [42], and logical thinking skills [43]. Although the description of scientific reasoning has also changed over time by several authors [42–50], a consensus among the authors is that scientific reasoning is a set of knowledge-dependent cognitive skills that are necessary for the creation and understanding of new scientific knowledge. The common opinion that scientific reasoning skills depend on prior learning reinforces the importance of science students' pre-existing conceptions, which Martin [51] defined as misconceptions.

1.4.2. *Misconceptions in science*

Scientific misconception can be defined as thoughts or beliefs that have no scientific basis or scientific understanding [52]. Misconceptions result in learning barriers to students learning science. One of the ways to identify misconceptions is through diagnostic assessments such as interviews [53], open-ended questions [54], multiple-choice tests [55], and multiple-tiered multiple-choice tests [56]. These authors found that the primary cause of misconceptions in science is content abstractness and complexity, which may be exaggerated by life experiences, textbook presentation of content, teacher quality and training, and differences in language used at home and school [57]. In a review of 111 studies, Soeharto [58] found that physics was the subject with the highest occurrence of science misconceptions and that multiple-tiered tests were the most effective in diagnosing the problem. One tool that may be used to distinguish between a misconception and a fundamental lack of knowledge is confidence [59].

1.4.3. *Confidence*

Self-confidence can have a positive effect on learning by allowing individuals to approach new tasks and challenges with a positive mindset, leading to better engagement and perseverance in the face of difficulties [60]. Self-confident learners may also be more likely to take risks and try new strategies when learning, leading to a deeper understanding of the material [61]. Conversely, low self-confidence can lead to a lack of motivation and a fear of failure, which can impede learning [62]. It is important to note that self-confidence is not the only factor that affects learning, and that other factors such as prior knowledge, cognitive abilities, and learning strategies also play a role [63].

A student's confidence rating of their answer to an item in a diagnostic test refers to their internal belief in the accuracy of their response [64]. Generally, high-performing individuals' confidence ratings match their ability more accurately, but poor-performing individuals tend to exaggerate their confidence [65]. These observations are exaggerated in science students [66]. Although there is no established correlation between confidence and reasoning ability, there are positive correlations between confidence and science performance [67,68]. The implication is, therefore, a higher likelihood of misconception when students respond with a higher confidence rating to a wrong answer [69–71]. The present study adapts the standard LCTSR by adding a variable of confidence to each LCTSR item, and the resulting three-tiered assessment instrument is used to explore student's misconceptions in science.

1.4.4. *Correlations between LCTSR dimensions*

In a sample of students Grade 9 level [31], calculated, at a 95% confidence level, significant positive correlations between the conservation of mass and volume, proportional reasoning, control of variables and, probability reasoning dimensions. No correlation was found between the correlational and hypothetical-deductive reasoning dimensions. The small sample size of 18 indicates that the findings may not be generalised. Another important finding of [31] is the strong correlation between scientific reasoning dimensions (proportional reasoning, control of variables, and probability reasoning) with test performance. This finding is also supported by Ref. [28]. In a sample of 446 students at the university entrance level [28], found low correlations (Spearman coefficients below 0.5) for all dimensions of the LCTSR. The findings also supported stronger correlations (Spearman coefficients above 0.6) between scientific reasoning dimensions (control of variables, probabilistic reasoning and, proportional reasoning) with performance. In a cross-grade study comprising 2669 students ranging from Grade 4 to Grade 16 [26], found similar weak correlation findings to Refs. [28,31]. The study's large scale and cross-grade nature allowed [26] to explore the progression of scientific reasoning skills from Grade 4 to Grade 16 level [26]. concluded that the progression of scientific reasoning ability increases rapidly during middle school, with the control of variables and hypothetical-deductive reasoning skills being the last to develop.

The present study explores the scientific reasoning skills of first-year university students. Therefore, according to Refs. [26,28], and [31], the scientific reasoning ability of the sampled students should indicate at least weak correlations between all of them.

1.4.5. *Validity of the LCTSR*

[3], in a study of 1576 first-year students from three midwestern public universities, found that five of the twelve pairs of LCTSR items did not meet the acceptable value of Cronbach's alpha of 0.65 required for consistent item response. Table 2 indicates the LCTSR item pairs and includes the Cronbach's alpha statistic reported in Ref. [3] (Table 3).

The items identified as having inconsistent responses were Items 7 and 8, 11 to14, and 21 to 24. Due to the inconsistent item response, the present study excluded the mentioned items. As a result, the present study includes only seven LCTSR paired items that belong to the conservation (Items 1 to 4), proportional reasoning (Items 5 and 6), control of variables (Items 9 and 10), probability (Items 15 to 18), and correlation reasoning dimensions (Items 19 and 20). The variables identified in the present study comprise responses to the context questions, explanation statements, and response confidence.

1.5. *Objectives*

The six objectives of the present study are to determine.

1. The coherence between scientific reasoning dimensions,
2. The relationship between knowledge and reasoning,
3. The relationship between reasoning dimensions and confidence,
4. The relationship between knowledge and confidence,
5. The relationship between reasoning and confidence, and
6. The insights from coherence in students' responses to the LCTSR.

1.6. *Research questions*

The research questions formulated to assist in achieving the objectives of the present study are.

RQ1. What is the coherence between scientific reasoning dimensions in LCTSR?

RQ2. What is the relationship between context questions and explanation statements in LCTSR?

RQ3. What is the relationship between reasoning dimensions and response confidence in LCTSR?

Table 2
Scientific reasoning dimensions of LCTSR.

Scientific Reasoning Dimensions	Context questions	Explanation statement	Cronbach's alpha
Conservation	1	2	*0.82
	3	4	*0.97
Proportional reasoning	5	6	*0.89
	7	8	*0.54
Control of variables	9	10	*0.92
	11	12	*0.46
	13	14	*0.38
Probability	15	16	*0.69
	17	18	*0.86
Correlation reasoning	19	20	*0.83
	21	22	*0.56
Hypothetical-deductive reasoning	23	24	*0.33

Note. *Cronbach's alpha $<$ acceptable value of 0.65 indicating inconsistent item response, the corresponding item pairs are excluded from the present study. Data obtained from Table 3, "Validity evaluation of the Lawson classroom test of scientific reasoning" by L. Bao, Y. Xiao, K. Koenig, and J. Han, 2018, *Physical Review Physics Education Research* 14, 020,106, https://doi.org/10.1103/PhysRevPhysEducRes.14.020106.

Table 3
Spearman's correlation results for scientific reasoning dimensions in LCTSR.

Dimension	Code	Dimension	Code	ρ	*p*
Probability	D4	Conservation	D1	0.4137	0.0004*
Probability	D4	Proportional reasoning	D2	0.3761	0.0013*
Probability	D4	Control of variables	D3	0.3555	0.0023*
Control of variables	D3	Conservation	D1	0.2919	0.0150*
Correlation reasoning	D5	Probability	D4	0.2789	0.0185*
Correlation reasoning	D5	Control of variables	D3	0.2346	0.0489*
Correlation reasoning	D5	Conservation	D1	0.1895	0.1188*
Proportional reasoning	D2	Conservation	D1	0.1663	0.1722*
Correlation reasoning	D5	Proportional reasoning	D2	0.1471	0.2243*
Control of variables	D3	Proportional reasoning	D2	0.0923	0.4475*

Note. N = 71. *$p < 0.05$ indicates statistical significance at the 95% confidence level.

RQ4. What is the relationship between knowledge and confidence in LCTSR?

RQ5. What is the relationship between understanding and confidence in the LCTSR?

RQ6. What are the insights from coherence in students' responses to the LCTSR?

2. Methods

This case study explores the insights learned from the coherence of students' responses to the LCTSR. A confidence variable is added to the standard LCTSR, which allows exploring student misconceptions in science [72,73]. To facilitate this exploratory case study, the adapted LCTSR investigates the correlations between dimensions of the LCTSR and student confidence. The results of the LCTSR may be affected by various factors, which include the student's prior knowledge and experience in science, language proficiency, test-taking anxiety and abilities, cultural and background experiences, and the learning and assessment environment. The study was designed to control for potential confounding factors by selecting participants with similar backgrounds, equivalent English proficiency, and the same level of prior scientific knowledge. The researchers also provided clear instructions to reduce testing anxiety and used standardized test administration with computer-based data collection techniques to ensure participant consistency. The following sections discuss the sample, coding scheme, confidence, statistical reporting, and limitations of the present study.

2.1. Sample

Data were obtained from 71 respondents that were sampled purposively based on geographic location and availability of researchers to administer LCTSR. The respondents were selected from two tertiary institutions, one academic and one technical institute, in two provinces in South Africa. 58% of the sample were male, and 57% were female, with an average age of 19 years and eight months. Most of the sample were first-year science or engineering faculty students whose language spoken in the home was Afrikaans (N = 23). Other languages spoken in the home included Setswana (N = 10), isiZulu (N = 9), English (N = 8), and Sepedi (N = 7). The standard LCTSR was administered in English to individual respondents who sat in front of the computer doing the LCSTR and answering each of the questions and giving their confidence rating. The computer-based LCTSR was integrated with Microsoft Excel® for data capture. The responses to each LCSTR content question, explanation statement, and confidence rating was coded according to the coding scheme.

2.2. Coding scheme

2.2.1. LCTSR items

The coding scheme of the present study is based on the work of [3]. The LCTSR uses a two-tier multiple choice (TTMC) scoring method in which the first tier corresponds to a context question (odd-numbered questions) that tests students' knowledge. The second tier corresponds to an explanation statement (even numbered questions) that tests students' understanding. Based on the TTMC of the LCTSR, the seven selected context questions were coded: Q1, Q3, Q5, Q9, Q15, Q17, and Q19. The seven selected explanation statements were coded: Q2, Q4, Q6, Q10, Q16, Q18, and Q22. The theoretical framework of the present study excluded the hypothetical-deductive reasoning dimension (coded G6), five context questions (coded Q7, Q11, Q13, Q21, and Q23), and five explanation statements (coded Q8, Q12, Q14, Q22, and Q24). Responses to context questions and explanation statements were recorded as bivariate data, assigned 1 for correct and 0 for incorrect responses. The coding and corresponding items of the five selected scientific reasoning dimensions of the LCTSR are.

- conservation (coded D1 and comprising Q1 to Q4);
- proportional reasoning (coded D2 and comprising Q5 to Q8);
- control of variables (coded D3 and comprising Q9 and Q10);
- probability reasoning (coded D4 and comprising Q15 to Q18); and

- correlational reasoning (coded D5 and comprising Q19 and Q20).

2.2.2. *Confidence items in the modified LCTSR*

In addition to capturing responses to the context questions and explanation statements, confidence responses were also captured. The confidence response for context questions and explanation statements were coded C1 to C20. Responses to confidence were recorded as ordinal data, assigned 1 for low confidence, 2 for medium confidence, and 3 for high confidence. The response confidence for each scientific reasoning dimension is a grouped variable and was calculated as the sum of the response confidence for each context question and explanation statement in the group. Therefore, the modified LCTSR coded the confidence responses for the other reasoning dimensions as.

- proportional reasoning, coded as CD2 and equal to the sum of C5 and C6.
- control of variables, coded as CD3 and equal to the sum of C9 and C10.
- probability reasoning, coded as CD4 and equal to the sum of C15, C16, C17, and C18.
- correlation reasoning, coded as CD5 and equal to the sum of C19and C20.

2.3. *Statistical reporting*

The statistical reporting for objectives 1, 4, and 5 include the Chi-square *p* for the significance of the correlation and Cramer's V statistic for the effect size of the effect. At the 95% confidence level a Chi-square p of less than 0.05 indicates a statistically significant correlation. The Cramer's V statistic ranges between 0 and 1, with values less than 0.3 indicating a weak correlation, 0.4 to 0.5 indicating a medium correlation, and greater than 0.5 indicating a strong correlation. The statistical reporting for objectives 2 and 3 includes Spearman's *p* for the significance of the correlation and Spearman's correlation coefficient (r) for the effect size. At the 95% confidence level, a *p* less than 0.05 indicates a statistically significant correlation. The r value ranges between 0 and 1 such that r values closer to 1 indicate a stronger correlation.

3. Results and discussion

3.1. *Coherence between scientific reasoning dimensions*

The discussion around the coherence between scientific reasoning dimensions answers the first research question (RQ1: What is the coherence between scientific reasoning dimensions in LCTSR?). Table 3 lists the results of the Spearman correlation test between the sampled scientific reasoning dimensions of the LCTSR.

Table 3 indicates that six of the ten pairs of scientific reasoning dimensions in LCTSR demonstrated statistically significant correlations. The probability dimension had the strongest correlation with the conservation, proportional reasoning, and control of variables with correlation coefficients of 0.41, 0.38, and 0.36, respectively. The present study's findings, which agree with [26,28], and [31], and indicate that students can use probability knowledge successfully in understanding concepts related to the scientific reasoning dimensions of conservation, proportional reasoning, and control of variables.

3.2. *Relationship between knowledge and understanding*

The discussion around the relationship between knowledge and understanding answers the second research question (RQ2: What is the relationship between context questions and explanation statements in LCTSR?). Table 4 presents the correct response and correlation data for context question and explanation statement pairs grouped by scientific reasoning dimension.

Table 4 shows the percentage of students who answered the context questions correctly and selected the correct explanation statement. A *p* of less than 0.05 for each scientific reasoning pattern indicates a statistically significant correlation between the context question and explanation statement pair for each scientific reasoning dimension. Q1 (conservation of mass) and Q19 (correlation reasoning) showed the highest percentage of correct responses. The majority of students knew that flattening a clay ball does not alter

Table 4
LCTSR responses and correlation results.

Dimension	Context items			Reasoning Items			*p*	ρ
	Item	CR (%)	IR (%)	Item	CR (%)	IR (IR)		
Conservation of mass	Q1	66.7	33.33	Q2	52.2	47.83	<0.05	0.74
Conservation of volume	Q3	34.8	65.22	Q4	30.9	69.12	<0.05	0.91
Proportional reasoning	Q5	13.0	86.96	Q6	15.7	84.29	<0.05	0.54
Control of variables	Q9	36.6	63.38	Q10	30.0	70.00	<0.05	0.81
Probabilistic reasoning	Q15	38.0	61.97	Q16	71.8	28.17	<0.05	0.43
Probabilistic reasoning	Q17	31.0	69.01	Q18	28.2	71.83	<0.05	0.60
Correlation reasoning	Q19	63.4	36.62	Q20	46.5	53.52	<0.05	0.24

Note. N = 71. [1]Context questions. [2]Explanations statements. CR = correct response. IR = Incorrect response.

its weight (Q1) because “clay has not been added or taken away” (Q2). In the question on correlational reasoning (Q19), 63.4% of students realised a link between the size of the mice and their tail colours, although size is not the sole determinant of the tail colour. Apart from the 46.5% of the students who chose the correct explanation in Q20, 32.4% chose an alternative incorrect explanation, indicating that those students incorrectly believe that other variables may affect the tail colour.

In all items other than Q1 and Q19, less than 50% of students displayed the required reasoning ability in the questions. For instance, only 34.8% answered Q3 on volume conservation correctly. Nearly half of the students (49.3%) incorrectly chose the alternative option that the water in a cylinder will rise higher when a steel marble (larger weight) is placed into it than would be the case with a glass marble. However, the question specifies that the marbles are the same size (i.e., volume). Students should have considered which variables (weight or size) would influence the total volume.

Q5 (13%) and Q6 (15.7%) showed the lowest correct responses in the proportional reasoning dimension, Q5 (13%) and Q6 (15.7%). Students’ most common mistake was applying addition instead of multiplication. Using addition indicates that students did not understand that the ratio of the water heights in cylinders of varying widths remains the same when pouring different amounts of water from one cylinder to the other.

For Q9, 36.6% of the students correctly indicated that the string length’s effect on the pendulum’s period requires the use of strings 1 and 2. However, only 30.0% provided the correct explanation. The most prevalent alternative was using all three strings in the experiment. These students needed to understand the requirement of keeping the weight constant to determine the relationship between the two other variables [74]. Q5 involves the concepts of chance and randomness and applies proportional reasoning and deficiencies in these reasoning skills may be why only 38.0% chose the correct option. Similar issues were evident for items Q17 and Q18, which required the student to calculate the probability of pulling out a red round or blue round piece from a set of blocks having different colours and shapes. Only 31.0% of students responded correctly, while only 22.9% gave the correct explanation. The low proportion of correct explanations indicates a need for more probabilistic reasoning skills.

For almost all item pairs, the percentage of correct responses to the questions was more significant than the explanations. An exception occurred for the probabilistic reasoning dimension, in which 71.8% of students chose the correct explanation statement Q16 compared to only 38.0% of students who responded correctly to Q15. A plausible explanation is that a student may have chosen the correct option (namely, “3 out of 6 pieces are red”) by applying either additive or multiplicative reasoning. The diagram is another method by which the student may have chosen the correct explanation statement even though the student did not understand probabilistic reasoning.

The results of the Chi-square correlation test indicate a statistically significant correlation between all context question and explanation statement pairs ($p < 0.05$). The identified correlations imply that students who answered a context question correctly were more likely to select the correct explanation statement. At the same time, students who did not respond correctly to the context question also selected the incorrect explanation statement. The largest correlation was observed for the conservation of volume dimension ($\rho = 0.91$, $p < 0.05$). The smallest correlation was observed for the correlation reasoning dimension ($\rho = 0.24$, $p < 0.05$). The results indicate that the student’s association between knowledge and understanding is the strongest in the conservation dimension and the weakest in the correlation reasoning dimension.

The present study finds that the lowest performance occurred in the proportional reasoning dimension. The findings of lowest performance in the proportional reasoning dimension is in agreement with [28,75]. Student responses indicate a need for more understanding of the multiplicative nature of proportionality. Even though students may report that one variable is directly proportional to another, they need to comprehend what it means. They also do not realise that proportionality exists only on the condition that all other possible variables are constant. Across all reasoning dimensions, the student’s responses indicate an inadequate scientific reasoning ability, particularly in the control of variables dimension. Only a third of students knew how to control variables scientifically in the formal physics context of the single pendulum. Most students did not keep the weight constant in determining the

Table 5
Correlation of context questions and explanation statements with confidence.

LCTSR Item	Confidence	p	Cramer’s V	Effect
Context questions				
Q1	C1	0.02	0.34	large
Q3	C3	0.43	0.16	medium
Q5	C5	0.43	0.15	medium
Q9	C9	0.10	0.26	medium
Q15	C15	0.25	0.20	medium
Q17	C17	0.07	0.28	medium
Q19	C19	0.14	0.24	medium
Explanation statements				
Q2	C2	0.00	0.45	large
Q4	C4	0.78	0.09	small
Q6	C6	0.30	0.19	medium
Q10	C10	0.00	0.46	large
Q16	C16	0.21	0.21	medium
Q18	C18	0.25	0.20	medium
Q20	C20	0.19	0.22	medium

Note. N = 71.

relation between the length and period of a pendulum. This lack of understanding of constant variables is also evident in the poor performance of questions related to the volume of a marble. Additionally, the quantity of water remains the same before and after submerging the marble into the water. Only the question related to the shape change indicated any positive measure of scientific reasoning ability. The majority of students successfully applied the conservation of mass under the transformation.

3.3. Relationship between knowledge, understanding and confidence

The discussion around the relationship between knowledge, understanding and confidence answers the third, fourth, and fifth research questions (RQ3: What is the relationship between reasoning dimensions and response confidence in LCTSR? RQ4: What is the relationship between knowledge and confidence in LCTSR? RQ5: What is the relationship between understanding and confidence in the LCTSR?). Table 5 shows the results for context questions and explanation statements correlated with confidence.

Table 5 indicates an overall medium correlation between context questions and confidence. The most significant correlation occurred in the conservation of mass dimension, which is also the dimension that received the highest proportion of correct responses. The calculation of a combined variable (QD) allows for the determination of the relationship between the joint LCTSR items and confidence (CD). QD for each dimension is a grouped variable comprising LCTSR questions and explanation statements (Q). Table 5 indicates the calculation of the combined LCTSR questions and explanation statements (QD) and confidence (CD) for each dimension.

Table 6 indicates an overall medium correlation between LCTSR items and confidence. The lowest correlation occurred in the proportional reasoning dimension. The small to medium statistical correlation between LCTSR items and confidence together with the high proportion of incorrect responses (Table 4), indicates that students were unknowingly confident despite their apparent lack of knowledge and understanding. The combination of being overconfident and consistently incorrectly responding to context questions and explanation statements indicates misconceptions and alternative reasoning processes. From an epistemological perspective, the reasoning dimensions assessed are connected in inquiry investigations and they all deal with variables and the relations between them. Inquiry investigations require the ability to recognise variables that may have an effect on the outcome of a phenomenon. The basis of inquiry investigations includes the ability to state hypotheses on possible connections between variables, design experiments using the control of variables strategy, and to interpret the relationships revealed by the results. The skill to control variables is central to an inquiry experiment [76] and is therefore closely associated with the other reasoning skills. For instance, aspects within the control of variables dimension extends to the correlation and probabilistic reasoning. The independent and dependent variables may be directly or inversely proportional to each other, indicating that proportional reasoning is required. The relationship between two variables can only be assessed if all other variables are kept constant in the experimental design. This shows that students do not understand the concept control of variables and rely on misconceptions rather than scientific reasoning as identified in Refs. [69,70], and [71]. Table 7 shows the correlation results for context questions, explanation statements and response confidence.

The data of Table 7 shows the correlation results for context questions, explanation statements and response confidence. The correlation between context questions and explanation statement provides insight on the coherence between knowledge and understanding. The correlation between context questions and explanation statements, and between explanation statements and confidence provides insight on reasoning ability and misconceptions. The data of Table 6 indicates a statistically significant strong relationship between context questions and explanation statements, $r\ (69) = 0.83$, $p < 0.05$. This implies that knowledge is highly correlated with understanding. However, there is statistically significant evidence that supports a weak correlation between context questions, $r\ (69) = 0.33$, $p < 0.05$ and understanding, $r\ (69) = 0.36$, $p < 0.05$, with response confidence. The findings indicate that some students responded with a high confidence level even though they did not have the required knowledge or understanding. One of the explanations for this correlation are stable misconceptions as found by Refs. [69,70], and [71].

3.4. The insights from the coherence of students' responses to the LCTSR

The discussion around the insights from the coherence of students' responses to the LCTSR answers the sixth research question (RQ6: What are the insights from coherence in students' responses to the LCTSR?). Scientific reasoning skills improve higher-order thinking [77] and it is therefore necessary to establish coherence in students' scientific reasoning. The evident lack of coherence between content questions and explanation statements (Table 6) provides insight into the lack of coherence between knowledge and understanding. The data of Table 6 supports particular deficiencies in students' scientific reasoning skills. Two of the dominant shortcomings in the students' scientific reasoning related to proportional reasoning skills and the ability to control variables. In particular, constant variables were neglected, in both the design of new experiments and to the analysis of outcomes in a given

Table 6
Correlation of joint context questions and explanation statements with confidence.

Dimension	Confidence	ρ	effect	*p*
QD1 = Q1+Q2+Q3+Q4	CD1 = C1+C2+C3+C4	0.2418	medium	0.0470*
QD2 = Q5 + Q6	CD2 = C5+C6	0.1428	small	0.2382
QD3 = Q9 + Q10	CD3 = C9+C10	0.2106	medium	0.0779
QD4 = Q15 + Q16 + Q17 + Q18	CD4 = C15 + C16 + C17 + C18	0.2731	medium	0.0212*
QD5 = Q19 + Q20	CD5 = C19 + C20	0.2484	medium	0.0367*

Note. N = 71. *$p < 0.05$ indicates a statistically significant correlation at 95% confidence level.

Table 7
Correlation results for context questions, explanation statements and response confidence.

Variable 1	Variable 2	r	*p*
Context question	Explanation statement	0.8139	0.0001
Context question	Confidence	0.3338	0.0044
Explanation statement	Response confidence	0.3625	0.0019

Note. N = 71.

experimental set-up. It is also evident that discrepancies exist between students' confidence levels and performance.

The lack of coherence between students' confidence level and performance (Table 6) indicates stable misconceptions that challenge teaching for conceptual change. A proposed method of developing students' scientific reasoning is the use of remedial activities [78]. The focus of a remedial teaching sequence requires a progression from the real-world context to conceptual contexts and finally to formal contexts. The remedial activities must emphasise the role and purpose of each reasoning skill in an inquiry experiment and the repetitive application of a particular reasoning skill in multiple contexts. The aim of the development of students' coherent reasoning in a scientific framework through the use of remedial activities, is the consistent recognition and application of the appropriate reasoning skill in various contexts and situations.

4. Conclusion

The study found that there is a statistically significant coherence between scientific reasoning dimensions in LCTSR which is matched by a strong positive correlation between context questions and explanation statements. The present study found strong correlations between the probability dimension and the conservation, proportional reasoning, and control of variables dimensions, but showed deficiencies with regard to the proportional and correlation reasoning dimension. The basis of the present study is that a correct response to a content-based question with an incorrect response to an explanation statement indicates a high degree of student misconception. A weak correlation between content statement responses, explanation statements responses, and confidence ratings is a measure of student's scientific misconceptions. The findings of the study indicate significant weak correlations between knowledge and confidence, and between understanding and confidence. Insights from the lack of coherence suggests possible misconceptions in students scientific reasoning skills.

Effective constructivist-based science teaching not only requires an understanding but also the coherence between students' knowledge and reasoning skills. The consistency of incorrect responses to the LCTSR indicates students' reliance on intuitive reasoning instead of an explanatory scientific framework. Consequently, deficiencies in some skills tend to hamper understanding of the others. To establish scientific coherence in students' reasoning ability, this study recommends an intervention study that employs a teaching sequence which starts by familiarizing students with the idea that several factors can simultaneously affect an outcome. The need for control of variables to determine the effect of one variable on another could then be established, after which several inquiry experiments, from simple to more advanced, could be performed. In every experiment, the role and place of each reasoning skill should be explicated as it is applied. As need arises, a particular skill can be focussed on and be repeated in a variety of contexts. Finally, students can be expected to coherently design their own inquiry experiments.

5. Limitations and recommendations

This study is limited to five of the six scientific reasoning dimensions of the LCTSR. The hypothetical-deductive reasoning dimension, which comprises Q21 to Q24 of the LCTSR, is excluded from the present study [3]. provided several reasons that support the exclusion of the hypothetical-deductive reasoning dimension. The context of the questions in the hypothetical-deductive reasoning dimension is related to complex experiments with multiple variables. The provided context requires a higher-than-usual cognitive demand, which may expand to assessing more than just scientific reasoning.

An example of the complex contextual issues is Q21, which proposes placing a balloon over a flame. Students' experiences may influence their thinking that a balloon, typically made from thin rubber, placed over a flame may cause damage to the balloon. The provided context renders the question infeasible. Both pairs of questions (Q21-Q22 and Q23-Q24) rely on a student disproving a hypothesis, contrary to experiments conducted in the school setting based on proving a hypothesis. Therefore [3], argued against the validity of the hypothetical-deductive reasoning dimension and is the basis for excluding this dimension from the present study. Based on the limitations of the present study, it is recommended that future research investigate the relationships between scientific reasoning and other constructs, such as critical thinking, problem-solving, and creativity. This research would help to understand the interplay between these constructs and provide insight into how they can be effectively taught and assessed.

Ethics statement

This study has been conducted in accordance with the ethical guidelines provided by the North-West University Ethics Committee. The research protocol was reviewed and approved by the ethics committee under approval number NWU-00053-14-A3. The study involved adult human participants and all necessary measures were taken to ensure the protection of their rights and welfare. Informed consent was obtained from all participants prior to their participation in the study. Participants were provided with a detailed explanation of the study's purpose, procedures, potential risks, and benefits, and they provided their consent willingly.

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Author contribution statement

Nishaal Bhaw: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Jeanne Kriek: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Miriam Lemmer: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Additional information

Supplementary content related to this article has been published online at [URL].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17349.

List of Abbreviations

C	Confidence
CD	Confidence reasoning dimension
CR	Correct response
D	Scientific reasoning dimension
GALT	Group Assessment of Logical Thinking Test
IR	Incorrect response
ISLA	International large-scale assessment
LCTSR	Lawson's Classroom Test of Scientific Reasoning
PISA	Programme for International Student Assessment
Q	Question
QD	Question reasoning dimension
RQ	Research question
TOLT	Test of Logical Thinking
TIMSS	Trends in International Mathematics and Science Study
TTMC	Two-tier multiple-choice

References

[1] V.A.S. Centurino, D.L. Kelly, TIMSS 2023 science framework, in: I.V.S. Mullis, M.O. Martin, M. von Davier (Eds.), TIMSS 2023 Sssessment Frameworks, TIMSS and PIRLS International Study Centre, 2021.

[2] M. Boon, M. Orozco, K. Sivakumar, Epistemological and educational issues in teaching practice-oriented scientific research: roles for philosophers of science, Eur. J. Philos. Sci. 12 (1) (2022) 1–23.

[3] L. Bao, Y. Xiao, K. Koenig, J. Han, Validity evaluation of the Lawson classroom test of scientific reasoning, PRPER 14 (2) (2018), 20106.
[4] L. Bao, K. Koenig, Y. Xiao, J. Fritchman, S. Zhou, C. Chen, Theoretical model and quantitative assessment of scientific thinking and reasoning, Phys. Rev. Phys. Educ. 18 (1) (Feb. 2022), 010115-1-010115–33.
[5] B. Wei, Z. Jiang, L. Gai, Examining the nature of practical work in school science textbooks: coverage of the diversity of scientific methods, Sci. Educ. 31 (4) (Aug. 2022) 943–960.
[6] M. Lemmer, J. Kriek, B. Erasmus, Analysis of students' conceptions of basic magnetism from a complex systems perspective, Res. Sci. Educ. 50 (2) (Apr. 2020) 375–392.
[7] A.J. Magana, S. Elluri, C. Dasgupta, Y.Y. Seah, A. Madamanchi, M. Boutin, The role of simulation-enabled design learning experiences on middle school students' self-generated inherence heuristics, J. Sci. Educ. Technol. 28 (4) (2019) 382–398.
[8] A. Ferreira, M. Lemmer, R. Gunstone, Alternative conceptions: turning adversity into advantage, Res. Sci. Educ. 49 (3) (2019) 657–678.
[9] S.-Y. Lin, C. Singh, Using isomorphic problems to learn introductory physics, PRST-PER 7 (2) (Aug. 2011), 020104-1–16.
[10] A. Basheer, N. Kortam, N. Zahran, A. Hofestein, M. Hugerat, Misconceptions among middle school students regarding the conservation of mass during combustion, Eurasia J. Math. Sci. Technol. 14 (7) (May 2018) 3109–3122.
[11] S. Shanta, J.G. Wells, T/E design based learning: assessing student critical thinking and problem solving abilities, Int. J. Technol. Des. 32 (1) (Mar. 2022) 267–285.
[12] E. Manz, R. Lehrer, L. Schauble, Rethinking the classroom science investigation, JRST 57 (7) (Sep. 2020) 1148–1174.
[13] S.-Y. Huang, Y.-H. Kuo, H.-C. Chen, Applying digital escape rooms infused with science teaching in elementary school: learning performance, learning motivation, and problem-solving ability, Think. Skills Creativ. 37 (Sep. 2020) 100681.
[14] K. Kleemola, H. Hyytinen, A. Toom, Exploring internal structure of a performance-based critical thinking assessment for new students in higher education, Assess Eval. High Educ. 47 (4) (May 2022) 556–569.
[15] A.E. Lawson, The development and validation of a classroom test of formal reasoning, J. Res. Sci. Teach. 15 (1) (1978) 11–24.
[16] V. Roadrangka, R.H. Yeany, M.J. Padilla, GALT - Group Test of Logical Thinking, Univ. Georg., Athens, GA, 1982.
[17] K.G. Tobin, W. Capie, The development and validation of a group test of logical thinking, Educ. Psychol. Meas. 41 (2) (Jul. 1981) 413–423.
[18] G.M. Kaygısız, B. Gürkan, U. Akbaş, Adaptation of scientific reasoning scale into Turkish and examination of its psychometric properties, Educ. Sci. Theor. Pract. 18 (3) (2018) 737–757.
[19] R. Rosdiana, P. Siahaan, T. Rahman, Mapping the reasoning skill of the students on pressure concept, J. Phys. Conf. 1157 (Feb. 2019), 0220361–5.
[20] A.S. Nur, S.B. Waluya, R. Rochmad, W. Wardono, Contextual learning with Ethnomathematics in enhancing the problem solving based on thinking levels, JRAMathEdu 5 (3) (Sep. 2020) 331–344.
[21] D. Van Vo, B. Csapó, Development of scientific reasoning test measuring control of variables strategy in physics for high school students: evidence of validity and latent predictors of item difficulty, Int. J. Sci. Educ. 43 (13) (Sep. 2021) 2185–2205.
[22] M. Othman, A. Osman, N. Abdullah, S.Z. Ahmad, Impact of student's programming experience on cognitive skills: towards a gamified multimedia learning approach, AJUE 18 (4) (Oct. 2022) 944–953.
[23] P.-J. Cheng, Y.-H. Liao, P.-T. Yu, Micro:bit Robotics Course: infusing logical reasoning and problem-solving ability in fifth grade students through an online group study system, IRRODL 22 (1) (Mar. 2021) 21–40.
[24] D. Musa, J.S. Mari, I.M. Mohammed, Emotional intelligence and reasoning ability as predictors to academic achievement of university students in North-Central Zone, Nigeria, JCER 20 (8) (2021) 75–88.
[25] L. Archambault, H. Leary, K. Rice, Pillars of online pedagogy: a framework for teaching in online learning environments, Educ. Psychol. (Jun. 2022) 1–14.
[26] L. Ding, Progression trend of scientific reasoning from elementary school to university: a large-scale cross-grade survey among Chinese students, Int. J. Sci. Math. 16 (8) (Nov. 2018) 1479–1498.
[27] N. Novia, S. Syamsu, R. Riandi, Student's Achievement in Lawson's Classroom Scientific Reasoning (LCTSR): the Effect of Gender and Age on Scientific Reasoning Ability, ICMScE, 2018, pp. 542–547.
[28] T. Hrouzková, L. Richterek, Lawson classroom test of scientific reasoning at entrance university level, in: Proceedings of the 4th International Baltic Symposium on Science and Technology Education, 2021, pp. 74–85.
[29] M. Luo, D. Sun, L. Zhu, Y. Yang, Evaluating scientific reasoning ability: student performance and the interaction effects between grade level, gender, and academic achievement level, Think. Skills Creativ. 41 (Sep. 2021).
[30] R.T. Novak, et al., Verbalized studying and elaborative interrogation in the virtual classroom: students with social anxiety prefer working alone, but working with a peer does not hurt their learning, JM&BE 23 (1) (Apr. 2022).
[31] E. Hejnová, P. Eisenmann, J. Cihlár, J. Pribyl, Relations between scientific reasoning, culture of problem solving and pupil's school performance, J. Effic. Responsib. Educ. Sci. 11 (2) (2018) 38–44.
[32] Y. Xiao, J. Han, K. Koenig, J. Xiong, L. Bao, Multilevel Rasch modeling of two-tier multiple choice test: a case study using lawson's classroom test of scientific reasoning, Phys. Rev. Phys. Educ. Res. 14 (2) (2018), 20104.
[33] S.A. Widodo, A.D. Pangesti, I. Istiqomah, K.S. Kuncoro, T.A. Arigiyati, Thinking process of concrete student in solving two-dimensional problems, Ekuivalen J. Pendidik. Mat. 14 (2) (Jun. 2020) 117–128.
[34] S. Im, A.K. Jitendra, Analysis of proportional reasoning and misconceptions among students with mathematical learning disabilities, J. Math. Behav. 57 (Mar. 2020) 100753.
[35] G. Nelson, J.H. Hunt, K. Martin, B. Patterson, A. Khounmeuang, Current knowledge and future directions: proportional reasoning interventions for students with learning disabilities and mathematics difficulties, Learn. Disabil. Q. 45 (3) (Aug. 2022) 159–171.
[36] U.I. Ogbonnaya, F.K. Awuah, Quintile ranking of schools in South Africa and learners' achievement in probability, Stat. Educ. Res. J. 18 (1) (May 2019) 106–119.
[37] A.E. Lawson, The nature and development of scientific reasoning: a synthetic view, Int. J. Sci. Math. 2 (3) (2004) 307–338.
[38] W. Trzebiński, B. Marciniak, There is no smoke without fire: how frequency information and the experience attribution make negative online restaurant reviews more harmful, PLoS One 17 (7) (Jul. 2022) 1–25.
[39] A. Suryadi, L. Yuliati, H. Wisodo, The effect of STEM-based phenomenon learning on improving students' correlational reasoning, in: AIP Conf. Proc. Proceedings, 2021, pp. 1–8.
[40] K.T. Wissman, A. Zamary, K.A. Rawson, When does practice testing promote transfer on deductive reasoning tasks? JARMAC 7 (3) (Sep. 2018) 398–411.
[41] S.S. Khemlani, R.M.J. Byrne, P.N. Johnson-Laird, Facts and possibilities: a model-based theory of sentential reasoning, Cognit. Sci. 42 (6) (Aug. 2018) 1887–1924.
[42] P. Chance, Thinking in the Classroom: A Survey of Programs, Teachers College Press, Illustrate. New York, 1986.
[43] R. Narode, M. Heiman, J. Lochhead, J. Slomianko, Teaching Thinking Skills: Science, National Education Association, Washington DC, 1987.
[44] M.C. Tama, Critical thinking has a place in every classroom, J. Read. 33 (1) (1989) 64–65.
[45] M.G. Hickey, Reading and social studies: the critical connection, Soc. Educ. 54 (3) (1990) 175–179.
[46] L.M. Mertes, Thinking and writing, Middle Sch. J. 22 (5) (May 1991) 24–25.
[47] R.E. Mayer, F.M. Goodchild, The Critical Thinker : Thinking and Learning Strategies for Psychology Students, Dubuque, Iowa: Wm. C. Brown, 1990.
[48] M. Scriven, R. Paul, Critical thinking defined, in: Critical Thinking Conference, 1992.
[49] R.H. Ennis, Critical thinking assessment 32 (3) (1993).
[50] M. Lipman, in: A. Ornstein CIER, L. Behar (Eds.), Critical Thinking - what Can it Be?, Allyn & Bacon, Boston, MA, 1995, pp. 145–152.
[51] R.E. Martin, C.M. Sexton, J.A. Gerlovich, Teaching Science for All Children: an Inquiry Approach, Allyn & Bacon, 2001.
[52] N. Hakimah, M. Muchson, H. Herunata, M.B. Permatasari, A. Santoso, Identification student misconceptions on reaction rate using a Google forms three-tier tests, in: AIP Conf. Proc., 2021, 020020-1–8.

[53] P.R. Murti, N.S. Aminah, Harjana, The identification of high school students' knowledge of Newton's law of science literacy using a test based on nature of science (NOS), J. Phys. Conf. 1153 (Feb. 2019) 1–6.

[54] A.S. Halim, S.A. Finkenstaedt-Quinn, L.J. Olsen, A.R. Gere, G.V. Shultz, Identifying and remediating student misconceptions in introductory biology via writing-to-learn assignments and peer review, CBE-Life Sci. Educ. 17 (2) (Jun. 2018) 17.

[55] N. Saenpuk, C. Ruangsuwan, Development of 8 students' scientific concept in cause of moon phase by using metacognitive strategy, in: AIP Conf. Proc., 2019.

[56] A. Ammase, P. Siahaan, A. Fitriani, A review of students' common misconceptions in science and their diagnostic assessment tools, J. Pendidik. IPA Indones. 8 (2) (Jun. 2019) 1–6.

[57] A. Widiyatmoko, K. Shimizu, Literature review of factors contributing to students' misconceptions in Light and optical instruments, IJESE 13 (10) (2018) 853–863.

[58] B.Csapó Soeharto, E. Sarimanah, F.I. Dewi, T. Sabri, A review of students' common misconceptions in science and their diagnostic assessment tools, J. Pendidik. IPA Indones. 8 (2) (Jun. 2019) 247–266.

[59] M. Lemmer, Nature, cause and effect of students' intuitive conceptions regarding changes in velocity, Int. J. Sci. Educ. 35 (2) (Jan. 2013) 239–261.

[60] A. Omidullah, S. Javed, Students' self-confidence and its impacts on their learning process, Int. J. Soc. Sci. 5 (1) (2020) 1–15.

[61] M.Y. Moradi, G. Toktam, A. Yasaman, The effect of anxiety, motivation and self-confidence in language learners' reading proficiency, NeuroQuantology 20 (16) (2022) 4966–4976.

[62] A. Rahimi, Investigating the contributing factors affecting high school students' self-confidence and the solutions for enhancement: a case study of Arabu Qala High School, Kandahar, Afghanistan, Am. Int. J. Soc. Sci. 4 (1) (2019) 35–45.

[63] J.-C. Hong, H.-S. Hsiao, P.-H. Chen, C.-C. Lu, K.-H. Tai, C.-R. Tsai, Critical attitude and ability associated with students' self-confidence and attitude toward 'predict-observe-explain' online science inquiry learning, Comput. Educ. 166 (Jun. 2021) 104172.

[64] D.-C. Yang, Investigating the differences between confidence ratings in the answer and reason tiers in fourth graders via online four-tier test, Stud. Educ. Eval. 72 (March) (Mar. 2022).

[65] J. Kruger, D. Dunning, Unskilled and unaware of it: how difficulties in recognizing one's own incompetence lead to inflated self-assessments, J. Pers. Soc. Psychol. 77 (6) (1999) 1121–1134.

[66] B.A. Lindsey, M.L. Nagel, Do students know what they know? Exploring the accuracy of students' self-assessments, PRPER 11 (2) (Jul. 2015) 20103.

[67] B. Finn, Metacognitive evaluations during science simulations: how do ratings of confidence and understanding relate to science assessment inquiry processes? Arch. Sci. Psychol. 6 (1) (Nov. 2018) 117–129.

[68] X. Wu, Q. Wu, Can students be more engaged and confident? A multiple membership multilevel analysis of science engagement and confidence and their effects on science achievement in East Asia, Stud. Educ. Eval. 73 (101147) (Jun. 2022) 1–12.

[69] I. Koto, S.E. Gusma, Using certainty response index to differentiate lack of knowledge and misconception about basic electrical concepts, J. Phys. Conf. 1731 (1) (Jan. 2021) 1–8.

[70] R. Grazziotin-Soares, et al., The interrelationship between confidence and correctness in a multiple-choice assessment: pointing out misconceptions and assuring valuable questions, BDJ Open 7 (1) (Dec. 2021) 10.

[71] H.E. Haryono, K.N. Aini, Diagnosis misconceptions of junior high school in Lamongan on the heat concept using the three-tier test, J. Phys. Conf. 1806 (1) (Mar. 2021) 1–6.

[72] S. Gao, J. Wang, Do variations of science teaching approaches make difference in shaping student content and problem solving achievement across different racial/ethnic groups? Int. J. Environ. Sci. Educ. 11 (12) (2016) 5404–5428.

[73] K.E. Matthews, P. Adams, M. Goos, Quantitative skills as a graduate learning outcome: exploring students' evaluative expertise, Assess Eval. High Educ. 42 (4) (May 2017) 564–579.

[74] C. Vásquez, Á. Alsina, Analysing probability teaching practices in primary education: what tasks do teachers implement? Mathematics 9 (19) (Oct. 2021) 2493–2541.

[75] R. Cahyaningrum, Lawson instrument: analyzing student's scientific reasoning skill in junior high school, in: ICCD 2019, 2019.

[76] S. Zhou, et al., Assessment of scientific reasoning: the effects of task context, data, and design on student reasoning in control of variables, Think. Skills Creativ. 1 (19) (2016) 175–187.

[77] A.H. Abdullah, N.L.Z. Abidin, M. Ali, Analysis of students' errors in solving higher order thinking skills (HOTS) problems for the topic of fraction, Asian Soc. Sci. 11 (21) (Jul. 2015) 133–142.

[78] S. Boubih, A. Aidoun, M. El Alaoui, R.J. Idrissi, The effectiveness of the flipped classroom in a teacher training context, Univers. J. Educ. 8 (11B) (Nov. 2020) 6061–6071.