The Development of a Measurement Instrument to Assess Student's Competence in Connecting the Multiple Representations in Chemistry on Acid-Base Titration

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The Korean Conference on Education 2024
Official Conference Proceedings

Abstract
The purpose of this research was to develop a measurement instrument to assess student's competence in connecting multiple representations in chemistry, specifically focusing on acid-base titration topics. The student's competency was categorized into three levels, ranging from Level 1, where students demonstrate a correct understanding of the concept of acid-base titration at the macroscopic, submicroscopic, and symbolic levels without connecting these levels, to Level 3, which indicates a complete and correct understanding of the concept and the ability to connect its relationships across all three levels of representation. The instrument comprised 11 items based on the defined competencies. Data were collected from 344 students in grades 11 and 12 at the high school level. The instrument was analyzed for reliability and validity using Rasch analysis. Results indicated that the standardized residual responses for the developed items met the criteria for local independence as defined by the Rasch model. When comparing the difficulties of items and students' abilities on the same scale, the discrimination of items and the reliability of items met the criteria. However, the Rasch analysis suggested the need for revisions of some questions in the instrument for further study. The measurement instrument could serve as a standardized test for assessing students' competence in connecting multiple representations in chemistry, specifically within the context of acid-base titration topics.

Keywords: Assessment, Acid-Base Titration, Multiple Representations in Chemistry, Rasch Model

Introduction

Thailand aims to transform the school curriculum from a standards-based curriculum to a competency-based curriculum, which focuses on a person's ability to use their knowledge, skills, attitudes, and characteristics to work or solve problems to achieve a certain level of success. Competencies are the sum of knowledge, skills, attitudes, attributes, and other abilities that enable an individual or group to succeed at work. The competency curriculum focuses on the behavioral expressions of students' practices that can be measured and evaluated (Treadwell, 2011). The goal of a competency-based curriculum is therefore to prepare citizens for the 21st century.

Chemistry is the branch of science that studies the properties of substances and changes. The key competency that learners should gain from studying chemistry is understanding and connecting the relationships of multiple representations in chemistry. The multiple representations in chemistry include: (1) the macroscopic level, involving chemical phenomena that can be seen or observed in everyday life; (2) the submicroscopic level, involving phenomena at the atomic and molecular levels to understand various phenomena; and (3) the symbolic level, which are symbols that represent chemical elements or phenomena such as chemical formulas or chemical equations (Johnstone, 2000; Taber, 2013; Talanquer, 2019). Designing learning activities to promote learners with competency to understand and link the multiple representations in chemistry is therefore a challenging task for chemistry teachers around the world (de Berg, 2012; Li & Arshad, 2014; Tümay, 2016).

Another challenge is designing test instruments that can assess students' competency in chemistry. Most chemistry tests are multiple-choice or a two-tier diagnostic test (Karsli Baydere, 2021; Lu & Bi, 2016), however, many studies have designed measuring instruments that focus on the understanding and ability to translate between the multiple representations in chemistry. A two-tier multiple-choice diagnostic instrument was developed to assess secondary school students' ability to use the multiple representations in chemistry to explain different types of chemical reactions (Chandrasegaran et al., 2007). Berg (2012) designed a test in a mixed form of multiple-choice with short-answer questions on the topic of solution. Additionally, Irby et al. (2016) used a card sort task as a tool to measure the learner's ability to relate between the multiple representations in chemistry at various levels of education. Nonetheless, Popova and Jones (2021) stated that there is still a lack of effective tools to measure students' competency to translate between the multiple representations in different chemistry content. Therefore, measurement instruments that can assess learners' competency to translate between the multiple representations in chemistry must be further developed.

Acid-base titration is an important topic in upper secondary and university chemistry curricula that students are required to study. The topic also connects conceptual knowledge of chemical reactions to practical experiments in the laboratory. In terms of the experiment, titration is a method to find the concentration of an unknown solution by reacting with a standard solution which is known to be a certain concentration. The results of the experiment can be linked to conceptual knowledge of stoichiometry to calculate the concentration of an unknown solution. However, Sheppard (2006) indicated that secondary school students often struggle to learn acid-base titration because the content requires an understanding of many concepts in chemistry, and if students lack some pieces of knowledge, it will be difficult to understand the topic. This is in line with Nyachwaya (2016) which argued that students lack the competency to use submicroscopic and symbolic representations to explain the concept of titration which leads to a misconception about the content (Widarti et al., 2016).

A literature review on measuring learners' understanding of acid-base titration topics showed that there were many types of instruments, such as a multiple-choice measurement developed from learners' misconceptions (Demircioglu et al., 2005), concept maps (Yaman & Ayas, 2015), and a combination of concept maps with creative exercises (Ye et al., 2020). However, no research was found to focus on the development of a tool to measure learners' competency to translate between multiple representations, particularly in acid-base titration topics. The main objective of this research is therefore to develop a measurement instrument to assess students' competency to connect the multiple representations in chemistry on acid-base titration topics. The main research question is "How effective is the measurement instrument in assessing students' competency to connect multiple representations in chemistry on an acid-base titration topic?" The research framework is presented in Figure 1.

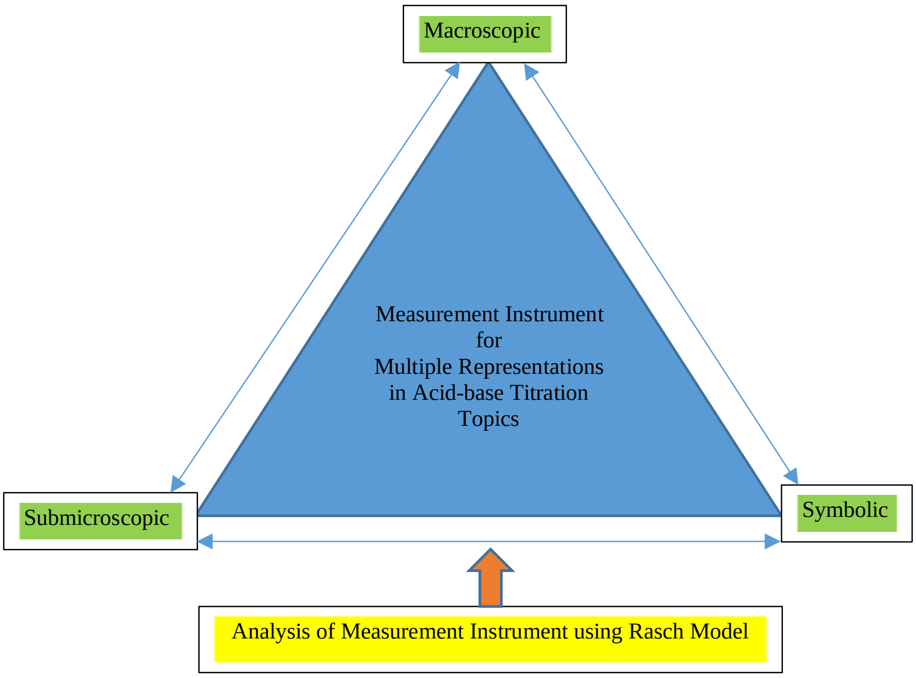


Figure 1: Research Framework

The Development of a Measurement Instrument

1. Defining the Competency Level

In this research, students' competence to connect multiple representations in chemistry on the acid-base titration topic is defined according to three levels (see Table 1) as follows:

Level 1: Students demonstrate a correct understanding of the concept of acid-base titration and representation at the macroscopic, submicroscopic, and symbolic levels, without connecting these levels.

Level 2: Students demonstrate a correct understanding of the acid-base titration concept and can connect its relationship to at least two levels of representations (macroscopic-submicroscopic, macroscopic-symbolic, and submicroscopic-symbolic).

Level 3: Students demonstrate a correct understanding of the acid-base titration concept and can connect its relationship in all three levels of representations (macroscopic-submicroscopic-symbolic).

Table 1: Defined the Competency Levels Related to Test Items

Level	Level Descriptions	Items
1	Students demonstrate a correct understanding of the concept of acid-base titration and representation at the macroscopic, submicroscopic, and symbolic levels, without making connections among these levels.	Q1, Q2, Q3, Q4
2	Students demonstrate a correct understanding of the acid-base titration concept and can connect its relationship to at least two levels of representations (macroscopic-submicroscopic, macroscopic-symbolic, and submicroscopic-symbolic).	Q5, Q6, Q7, Q8, Q9
3	Students demonstrate a correct understanding of the acid-base titration concept and can connect its relationship in all three levels of representations (macroscopic-submicroscopic-symbolic).	Q10, Q11

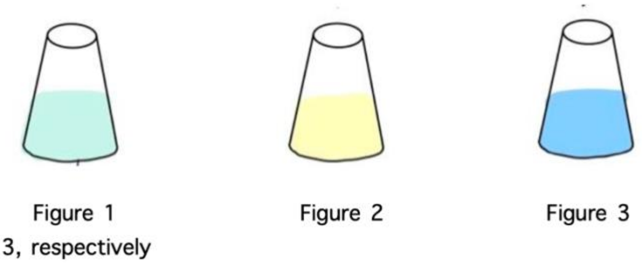
2. Development of Measurement Questions

18 questions were developed to begin with before all questions were tested for the index of item-objective congruence (IOC) based on the chemistry content and the level descriptions by three experts in chemistry education from university and high school levels. According to the IOC result, 11 items were chosen to develop the test in this study. There are four items aligned with level 1 (see Figure 2), five items aligned with level 2 (see Figure 3), and two items aligned with level 3 (see Figure 4).

3. Data Collection

The sample consisted of 344 high school students in a science-mathematics program that was obtained using purposive sampling. The students were required to hold prior knowledge about acid-base titration.

An experiment was conducted by dropping bromothymol blue into sample solutions, yielding the following results. (Given that the pH range for the color change of bromothymol blue is 6.0-7.6, where the color changes from yellow to blue). Which solution should have pH = 4.20, pH = 7.00, and pH = 10.50, respectively?



A. Figures 1, 2, and 3, respectively
B. Figures 3, 2, and 1, respectively
C. Figures 2, 1, and 3, respectively
D. Figures 3, 1, and 2, respectively

Figure 2: Example of Items Aligned With Level 1 (Macroscopic)

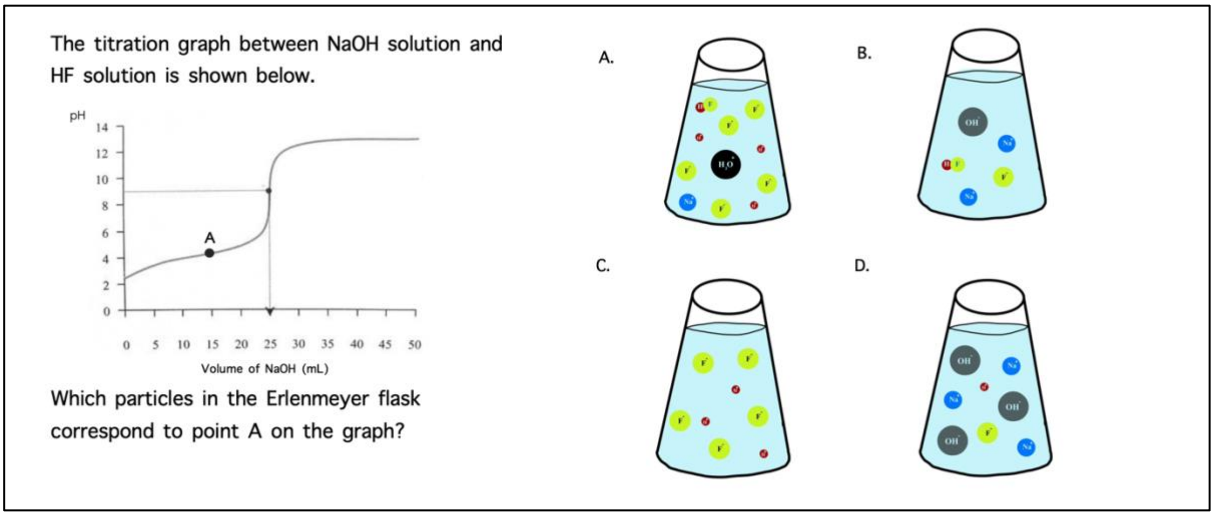


Figure 3: Example of Items Aligned With Level 2 (Submicroscopic-Symbolic)

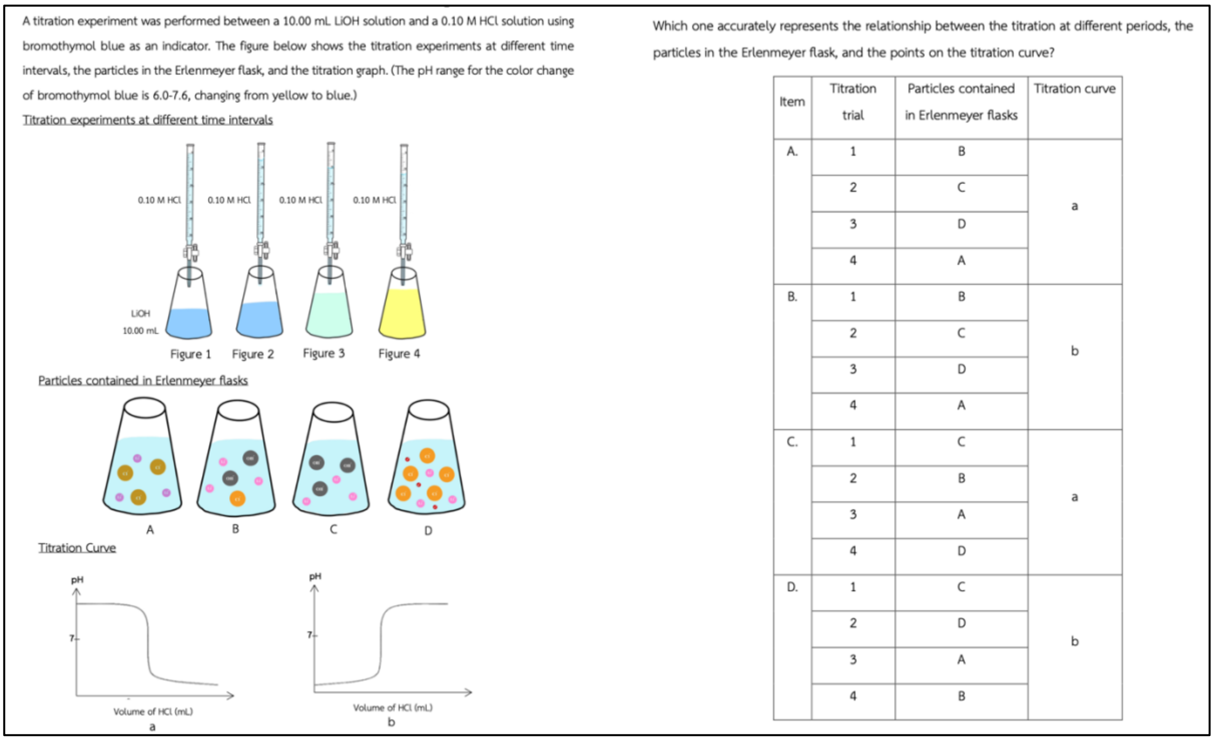


Figure 4: Example of Items Aligned With Level 3 (Macroscopic-Submicroscopic-Symbolic)

4. Analysis of Measurement Instrument

The raw data was used to analyze the validity and reliability of the measurement instrument based on the Rasch model by Winsteps 5.6.3 software. Rasch analysis is a psychometric model used to analyze data from assessments, particularly multiple-choice tests or questionnaires, based on item response theory. Rasch analysis helps refine test items and ensure their reliability. It measures both a person's ability and item difficulty on a common scale (logit scale).

Results and Discussion

The Rasch model was used to analyze the raw data of 344 students’ scores to estimate the difficulty of the items and the student's abilities on the same scale. The fundamental requirement for the Rasch model is unidimensionality, in which all items forming the test should measure only a single construct. In this paper, the unidimensionality was tested by the principal component analysis of contrast loadings of residuals. The variance explained 17.9%, indicating that the developed instrument was not unidimensional. Considering Figure 5, the standardized residual contrast plot (contrast loading) is within the range of -0.4 to +0.4 (Lu & Bi, 2016; Wang, Chi, Luo, Yang & Huang, 2017), indicating that most of the items were within the range. Four items beyond the range included A-Q4, B-Q2, a-Q1, and b-Q11 which had to be considered again. However, since all the items were below 0.7, the responses for the items developed thus met the criteria for local independence as defined by the Rasch model (Lu & Bi, 2016).

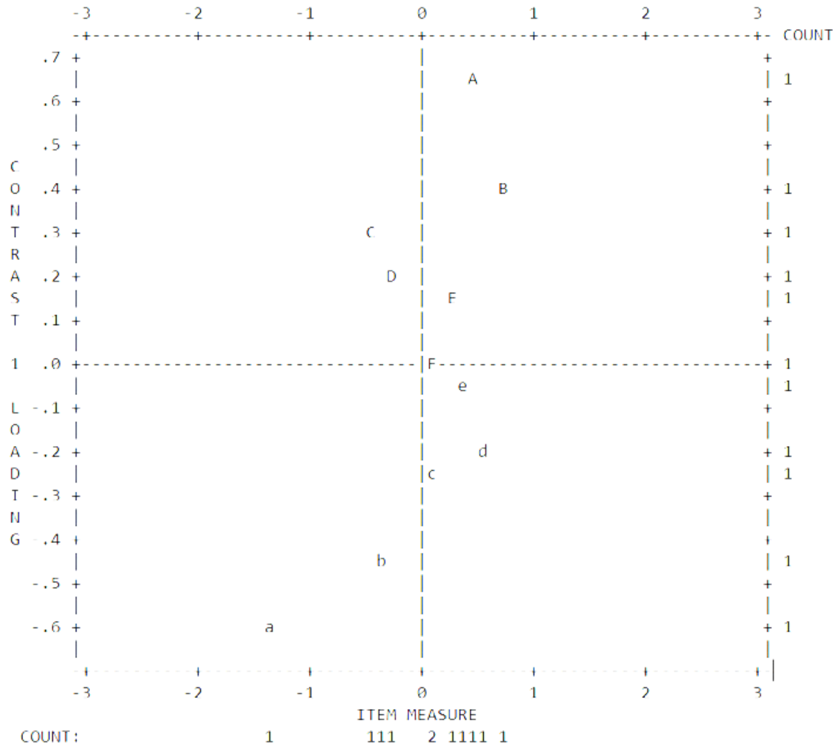


Figure 5: The Standardized Residual Contrast Plot

Table 2 presents the measure of 11 items in this instrument that relate to item difficulty. The item difficulties measured in the Rasch range from -1.35 logit to 0.69 logit, with low logit indicating an easier item than one with high logit. Another statistic of Rasch analysis is item fit, which shows how well the item aligns with the expectations of the Rasch model. There are outfit and infit of the mean square residual (MNSQ) and outfit and infit of the standardized mean square residual (ZSTD). From the analysis, it was found that outfit and infit MNSQ were within the range of 0.6 to 1.4, which ensures the items are suitable to be measured (Bond & Fox, 2007). In addition, the outfit and infit ZSTD was also in the range of -2 to +2 (Bond & Fox, 2007; Wei et al., 2012). According to the literature, if the outfit and infit MNSQ are within the range, the outfit and infit ZSTD can be disregarded (Linacre, 2018). It can therefore be concluded that all items are accepted to be a good fit according to the Rasch model. PTMEA CORR. refers to the correlation between the student scores and the person measure (score in logit). From the analysis, all the PTMEA CORR. values are positive and not close to zero, indicating that there are acceptable (Bond, 2015).

Table 2: Item Fit Statistics

Item	Measure	Model S.E.	Infit		Outfit		PTMEA corr.
			MNSQ	ZSTD	MNSQ	ZSTD	
Q2	0.69	0.14	1.12	1.66	1.21	1.87	0.20
Q9	0.51	0.13	1.09	1.45	1.21	2.06	0.23
Q4	0.43	0.13	0.87	-2.15	0.80	-2.36	0.47
Q3	0.38	0.13	1.03	0.59	1.09	1.03	0.30
Q10	0.25	0.12	0.97	-0.60	0.95	-0.62	0.39
Q6	0.10	0.12	0.92	-1.55	0.91	-1.30	0.43
Q8	0.09	0.12	0.94	-1.32	0.96	-0.54	0.42
Q7	-0.29	0.12	0.96	-0.95	0.92	-1.41	0.42
Q11	-0.36	0.12	0.97	-0.74	0.96	-0.69	0.41
Q5	-0.47	0.12	1.09	2.14	1.11	2.00	0.29
Q1	-1.35	0.12	1.02	0.4	1.00	0.09	0.37

Figure 6 shows the Person-Item Map or the Wright map, which is a visual representation of item difficulties and person abilities on the same scale called logit scale. An individual's abilities are plotted on the left side of the Person-Item Map, and the item difficulty consisting of 11 items is plotted on the right side. The Person-Item Map shows the locations of an individual's abilities and item difficulty in the same logit scale that the range of measure shown in the graph is -3 to 3 logit. On the left side, the '#' symbol represents 6 students, and the symbol '.' represents 1 to 5 students. On the right side, the items' difficulty is arranged from easy to difficult from bottom to top. The Wright map indicates that Q2 is the most difficult item in this instrument, while Q1 is the easiest item. According to the map, the individual's ability (on the left) estimates are located lower than the item's difficulty (on the right) indicating that some items are difficult for participants. Considering the gap between a person's abilities and the item map, there are two big gaps between Q1 and Q5, and Q6-Q8 and Q7 which means no test items can classify students' abilities within this range. The model suggests that more items should be developed to address the gaps in students' abilities for the next implementation.

When focusing on the alignment between measured item difficulty and defined levels, there are some mismatched items. Item Q2 (see Figure 7) is proposed to align with a submicroscopic in level 1, but the results indicate it to be the most difficult item. Some students failed to complete this item, which could be caused by a mismatch with the element symbol on the atom. Moreover, item Q9 (see Figure 3) which was proposed to align with level 2, was also difficult for students. The students may have made mistakes because the question asks about the product of the reaction of weak acid (HF) and strong base (NaOH) in terms of the submicroscopic related to the titration curve. It is noted that the two most difficult items were related to the submicroscopic level, which has been extensively documented in the literature as challenging for students to understand within chemistry (Laohapornchaiphan & Chenprakhon, 2024). Other items, such as Q3 (see Figure 8) and Q4 (see Figure 9), were difficult for participants because the questions deal with mathematics and require students to do arithmetic expressions to solve the problems. The students may have made calculation errors because they may not have understood the meaning of mole ratios in the balanced chemical equation concept, which was proposed to be one of the most challenging concepts in chemistry (Dahsah & Coll, 2007). For item Q4, the students may have had difficulty distinguishing the difference between pH and pOH values. These results provide useful information that can be used to revise questions in the future study.

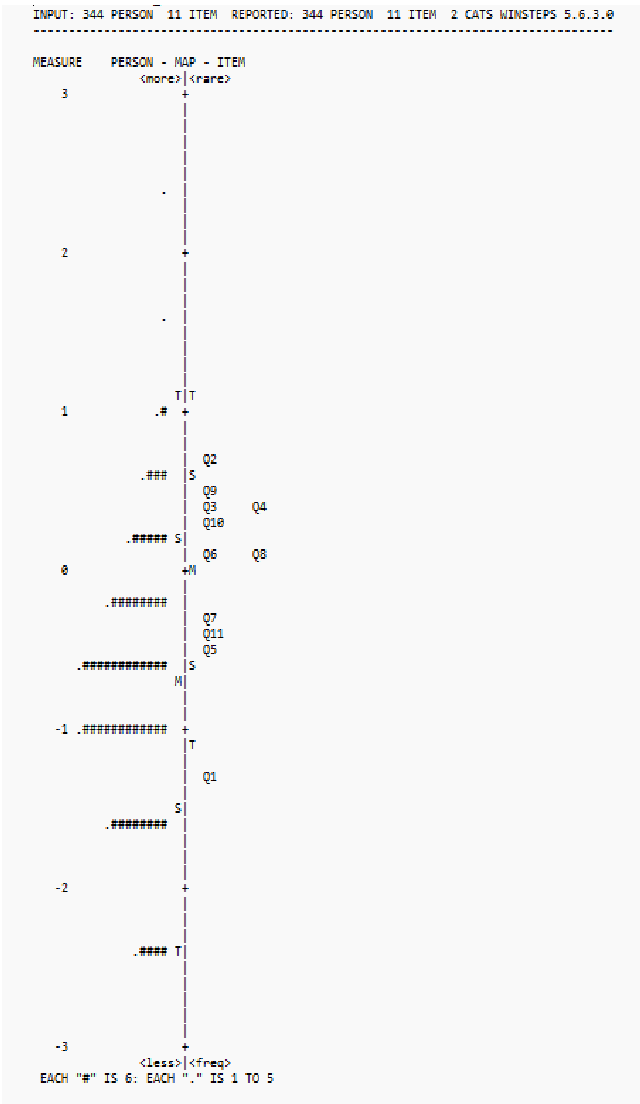


Figure 6: Person and Item Estimate Map (Wright Map)

In the titration experiment between a potassium hydroxide (KOH) solution and a hydrobromic acid (HBr) solution, which option correctly represents the particles in the Erlenmeyer flask at the equivalence point?

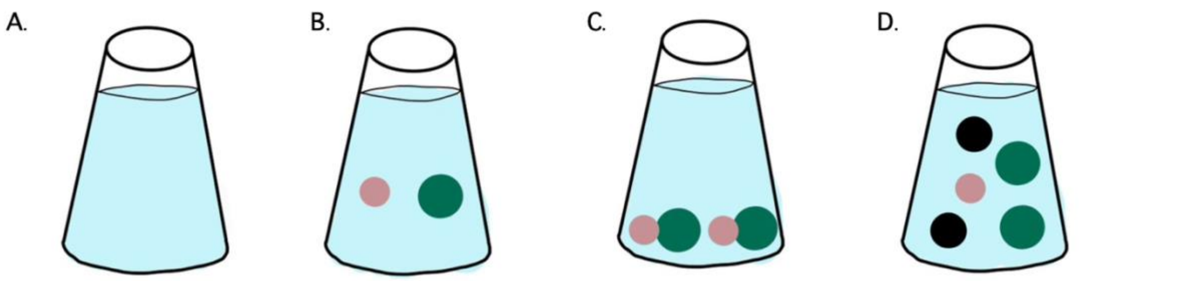


Figure 7: Item Q2

In the titration of 50.00 mL of unknown H_2SO_4 solution with 0.10 M NaOH solution, it was found that 50.00 mL of NaOH solution was required to reach the equivalence point. What is the concentration of the H_2SO_4 solution used in the titration?

A. 0.010 M B. 0.050 M C. 0.10 M D. 0.50 M

Figure 8: Item Q3

In the titration of 0.010 M HCl solution with 10.00 mL of unknown NaOH solution, it was observed that 10.00 mL of HCl was used to reach the equivalence point. Calculate the pH of the NaOH solution before the titration.

A. pH = 2.00 B. pH = 5.00 C. pH = 10.00 D. pH = 12.00

Figure 9: Item Q4

Table 3 presents a calculation of the mean measures (in logit scale) at each level of understanding defined in this study. According to the Rasch analysis, Q2 and Q9 were eliminated because both items were not aligned to the defined level that must be further revised. Using the results, the students' abilities can be divided into three groups. When the students' ability value was lower than -0.05, it was concluded that students' ability was below level 1 which means they were unable to demonstrate a correct understanding of the concept of acid-base titration and representation either at the macroscopic, submicroscopic, or symbolic levels. When students' ability was in the range of -0.05 to -0.01, it was concluded that they were at level 1, meaning they could demonstrate a correct understanding of the concept of acid-base titration and representation of at least one of the macroscopic, submicroscopic, and symbolic levels, without connecting these levels. When the students' ability was between -0.01 to 0.09, it was concluded that the students' ability was at level 2, meaning they could demonstrate a correct understanding of the acid-base titration concept and could connect its relationship to at least two levels of representations, for instance between the macroscopic and the submicroscopic levels, between the macroscopic and symbolic levels, or between the submicroscopic and symbolic levels for acid-base titration. When the students' ability was greater than 0.09, it was concluded that students' ability was at level 3, meaning they could demonstrate a correct understanding of the acid-base titration concept and could connect its relationship at all three levels of representations (macroscopic-submicroscopic-symbolic).

Table 3: Mean Measures of Understanding Levels After Excluding Items 2 and 9

Level	Items, measure	Mean measures
1	Q1(-1.27), Q3(0.54), Q4(0.59)	-0.05
2	Q5(-0.35), Q6(-0.25), Q7(-0.16), Q8(0.23)	-0.01
3	Q10(0.41), Q11(-0.23)	0.09

Table 4 presents a summary of the statistics from the measurement instrument which includes person and item measures, fit statistics, person and item separation, and person and item reliability. Generally, the mean of the item measure is normally set at 0. The table shows the mean of the person was -0.68, which is lower than the mean of item difficulty. This indicates that the measurement instrument was difficult for selected students. Analysis of the separation of person and item shows the person separation index was 0.67 and the item separation index was 4.27. Item and person separation index values greater than 2.00 indicate they met the recommended criteria (Bond & Fox, 2007). Although the item separation index is acceptable, the person separation index needs to be considered because it is below 2.00. The person reliability index is 0.31, and the item reliability index is 0.95. The item reliability is categorized as acceptable if such a value is higher than 0.8 (Bond & Fox, 2007). In contrast, the person reliability value was low, indicating weak correlations among students' responses to the items (Lu & Bi, 2016).

Table 4: Statistical Summary of Persons and Items

Parameter (*N*)	Measure	Infit		Outfit		Separation	Reliability
		MNSQ	ZSTD	MNSQ	ZSTD		
Person (344)	-0.68	1.00	0.05	1.01	0.08	0.67	0.31
Item (11)	0.00	1.00	-0.10	1.01	0.00	4.27	0.95

Conclusion

The core contribution of this research lies in the development of a measurement instrument designed to assess student's competence in connecting multiple representations of chemistry in the context of acid-base titration. Utilizing the Rasch model for analysis, the study scrutinizes the validity and reliability of the instrument, shedding light on its strengths and areas for improvement. The findings indicate certain challenges in achieving unidimensionality. The standardized residual responses for the developed items met the criteria for local independence as defined by the Rasch model. The item reliability and separation indices exceeded the recommended thresholds, indicating that the items were well-calibrated and capable of distinguishing between their levels of difficulty. However, the person separation and reliability indices fell below acceptable levels, suggesting limited effectiveness in differentiating among students' abilities and weak correlations in their responses. Furthermore, the mean person measure being lower than the item mean highlights that the instrument posed a considerable challenge for the selected students. These findings underscore the need for refinement of the measurement tool to enhance its sensitivity and alignment with the target population's abilities and some items require reconsideration for the next implementation.

Acknowledgements

The authors acknowledge the research support from the Research Grant for New Scholar, fiscal year 2022 from the Faculty of Science, King Mongkut's University of Technology Thonburi.

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