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Assessing High School Students’ Conceptual Understanding of Physics: A Cognitive Approach

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Abstract: This study used a descriptive quantitative method and mainly aimed at putting forward the idea that the select-and-fill-in (SAFI) concept maps could be used as a valid instrument to assess the conceptual understanding of thermodynamics among students. For this purpose, the concurrent validity of the SAFI concept map was evaluated according to the Thermodynamic Concept Survey (TCS) in order to develop a standard conceptual assessment test in thermodynamics. The TCS had a total KR-20 of approximately 0.78, an acceptable value, which could be employed as a valid test to assess the expert-developed SAFI concept map in this study. The study population included 60 students from two physics classes. An evaluation of the conceptual understandings of thermodynamics students was made concurrently using two assessment tools. Results showed that there is a moderate to strong correlation (0.6) between the SAFI concept map and TCS. This leads us to the conclusion that SAFI concept maps are valid tools, at least, as a complementary test in science classrooms.

Keywords: concept map, assessment, conceptual understanding, physics, high school

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Introduction

Thermodynamics is considered one of the most fundamental topics in physics and chemistry encountered by many students at different educational levels (Dreyfus et al., 2015; Saricayir et al., 2016). Nevertheless, many of the core concepts in thermodynamics are considered to be abstract and difficult for novices to grasp and usually bound in misconceptions for students (Anderson et al., 2005; Cox et al., 2003; Dukhan, 2016; Mulop et al., 2012; Schönborn et al., 2014; Sokrat et al., 2014). These misconceptions hinder students from acquiring a conceptual understanding of thermodynamics concepts and cause many difficulties for them to grasp the scientific ideas behind them (Saricayir et al., 2016).

Many scholars state that to promote conceptual understanding in science one needs to determine and solve these misconceptions through appropriate assessment and remedial approach (Clement et al., 1989; Halim et al., 2018; Kaltakci-Gurel et al., 2016; Sözen & Bolat, 2011; Weingartner & Masnick, 2019). Appropriate interpretations of students' existing conceptions might help educators design teaching approaches targeting conceptual understanding (Edwards, 2013). Scholars argued that in most cases, the focus of student evaluation is on propositional knowledge, which is aimed at determining the level of content and factual knowledge they have mastered, not the degree to which they have developed a well-integrated understanding (Edmondson, 2005; Shavelson & Ruiz-Primo, 1999). However, for propositional knowledge to be usable, the information needs to be interrelated conceptually (Kauertz & Fischer, 2006) to produce highly structured mental models such as experts (Toker & Moseley, 2013). Therefore, alternatives to traditional achievement tests must be sought, which probe mental models by eliciting the structural aspect of scientific knowledge.

In this regard, concept maps proved to be useful for portraying learning that traditional methods of assessment have not captured effectively (Edmondson, 2005; Stoddart et al., 2000). According to Novak and Cañas (2008), concept maps are tools for organizing and representing knowledge, which consist of nodes representing concepts and labelled lines denoting the relationship between pairs of nodes. Trowbridge and Wandersee (1996) found concept mapping to be a "highly sensitive tool for measuring changes in knowledge structure" (p. 54), particularly for depicting changes in students' selection of superordinate concepts, which have a significant impact on students' conceptions of the subject matter.

However, despite its benefits, concept mapping is challenging when applied in classrooms. Concept maps are considered ill-structured tasks since different correct solutions are possible (Jonassen, 1997). In science education, concept maps are regarded as cognitively demanding tasks given the cognitive efforts they require in order to recognize the concepts related to the subject and the relationships among them (Pérez Rodríguez et al., 2009; Schau & Mattern, 1997).

Several types of support have been considered to ease the cognitive demands of drawing concept maps, in terms of providing the concepts (Farrokhnia et al., 2019), linking phrases (Yin et al., 2005), and fill-in maps (Ruíz-Primo, 2000; Schau et al., 1997). In the latter, by keeping an expert-drawn concept map structure intact, some or all of the concept words and/or linking words are omitted. Students fill in these blanks either by generating the words to use or by selecting them from a set that may or may not include distractors, which is called Select And Fill In (SAFI) concept maps (Schau et al., 2001).

Some attempts have been made to use SAFI concept maps (Hassanzadeh et al., 2016; Hatami et al., 2016; Naveh-Benjamin et al., 1995; Turan-Oluk & Ekmekci, 2018), but so far, no study has been found to evaluate their validity as an assessment tool in science classes. As a result, in this study, by considering the importance of thermodynamics in science education, we attempt to evaluate the validity of SAFI concept maps for assessing the conceptual understanding of thermodynamics. This is done by making a comparison with the Thermodynamic Conceptual Survey (TCS) (Wattanakasiwich et al., 2013) as a valid concept inventory test for evaluating the students' conceptual understanding of thermodynamics. Therefore this study mainly seeks to answer this question:

Research question: What is the correlation between students' scores in the SAFI concept map assessment test and TCS?

Methodology

Participants

The participants ($N = 60$) were eleven-graders enrolled in the physics course at an Iranian high school. All the participants were males, and their average age was 16 years. The students were randomly divided into two groups of 30 students, which groups were randomly assigned to one of the assessment tests, i.e., SAFI concept map and TCS.

Materials

Concept inventory test

Concept inventories are test-based assessments of a concept or set of concepts, usually using multiple-choice questions (Furrow & Hsu, 2019). The incorrect choices for a question are ideally based on common student misconceptions (Sadler et al., 2010). Therefore, at their most useful, concept inventories can be used to diagnose areas of conceptual difficulty prior to instruction, and evaluate changes in students' conceptual understanding (Sands et al., 2018).

The present study employs a concept inventory test, which is the product of a study carried out by Wattanakasiwich and her colleagues (2013). In their study, they have developed the TCS containing 35 multiple-choice questions that assess students' understanding of the different concepts and principles related to thermodynamics, such as temperature, heat transfer, the ideal gas law, different processes, and the first law of thermodynamics. To determine the internal consistency (i.e., reliability) of the survey, Wattanakasiwich et al. (2013) utilized the Kuder-Richardson formula 20 (KR-20). The computed KR20 of the test was .78. According to Ding and Beichner (2009), one should attempt to generate a KR20 reliability coefficient of .70 and above to acquire a reliable score. This value of KR20 appears to be reliable, thus revealing that the TCS is a reasonably reliable instrument. Also, Ferguson's Delta (δ) determines the discriminating ability of the whole survey by measuring how broadly it spreads the distribution of scores. The valid value range for Ferguson's Delta is from 0.0 to 1.0, and the survey is considered to provide adequate discrimination when $\delta > .9$ (Ding & Beichner, 2009). In their study, each group had δ value above .9; therefore, based on both the item analysis and the whole survey analysis; the TCS is considered to be a valid and reliable test. Furthermore, the reliability of the TCS is also confirmed in the present study (KR-20 = .71), by employing the test in a pilot study with 35 students.

SAFI reference map

In order to use the SAFI concept map as an assessment tool, we need a reference map that serves as a criterion for measuring student's conceptual knowledge about the target domain by determining those propositions (nodes and links) that are deemed "substantial" and students are expected to know about a topic at a particular point. In this line, we utilized the SAFI concept map produced by experts in the given domain. In generating a SAFI reference map, it is assumed that: (1) there is some "agreed-upon organization" that sufficiently demonstrates the structure of a content domain, (2) "experts" in that domain can settle on the structure, and (3) concept maps of the expert offer an acceptable representation of the subject domain (Ericsson, 1996). We followed Ruiz-Primo et al.'s (2001) seven steps to develop our reference map of thermodynamics (Figure 1).

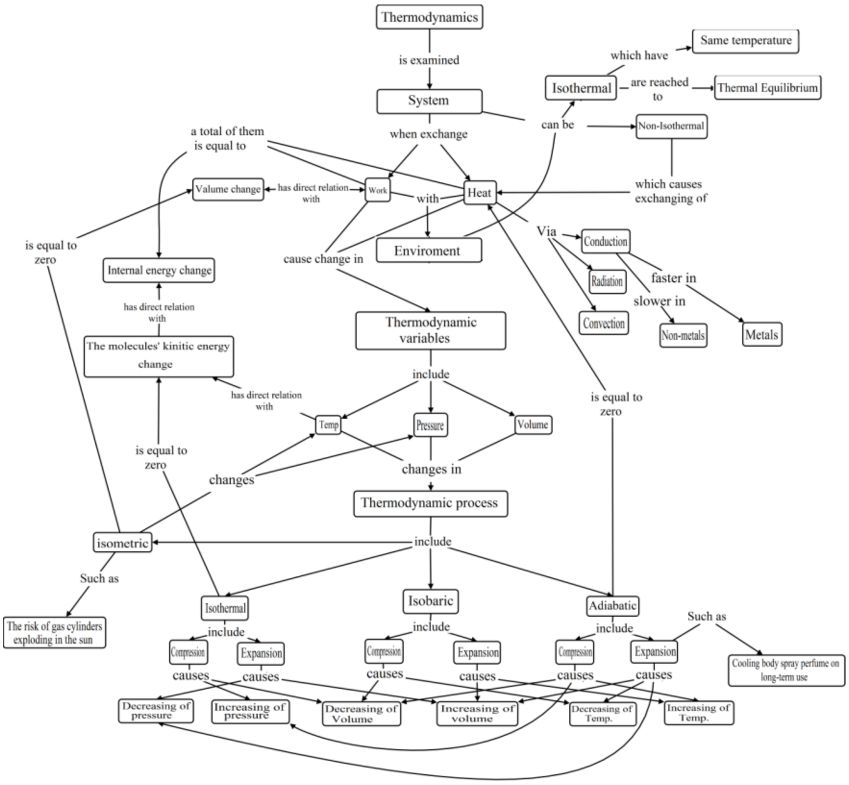

Figure 1. Reference map of Thermodynamics developed by the expert panel.

In general, SAFI formats are created in two steps: (1) the creation of a reference map by an expert panel, and (2) the omission of some or all of the concepts or linking phrases by the experts. Afterwards, the students are asked to fill in the blanks by choosing from a list of provided concepts (Schau et al., 1997). As a result, we omitted 33 concepts from the original map to develop our conceptual assessment tool, i.e., the Thermodynamics SAFI concept map (Figure 2).

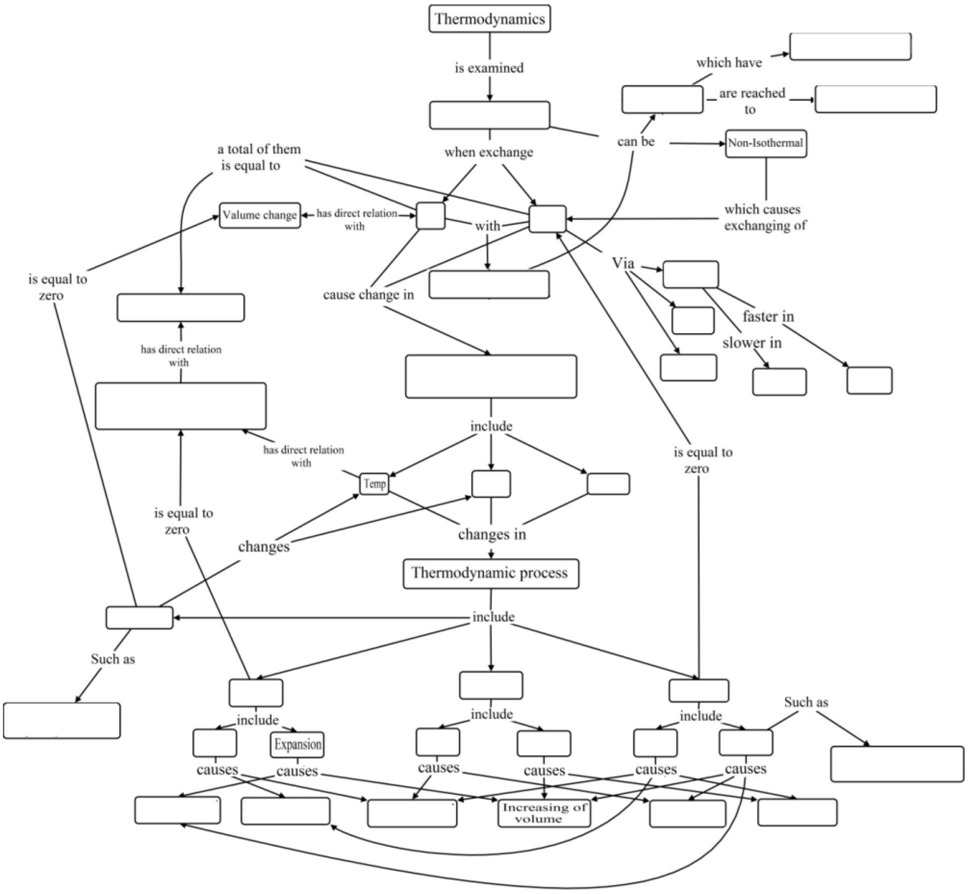

Figure 2. Thermodynamics SAFI concept map

KR-20 was used to evaluate the reliability of the final SAFI concept map. The map was examined with 35 students who had not participated in our study. The measured reliability was 0.887, which is an acceptable value.

Procedure

As previously mentioned in the introduction, the main goal of the present study is to examine the validity of the SAFI concept maps as evaluative tools for assessing students' conceptual understanding of thermodynamics at the high school level. The validation was assessed in two phases. In the first phase, content validity was assessed. As the SAFI concept map was made by the expert panel, it can be concluded that a final map is a valid tool for evaluating the conceptual understanding of students in the field of thermodynamics. Furthermore, the final map is also consistent with the curriculum objectives. In the second phase, concurrent validity was assessed. Concurrent validity is established by demonstrating high correlations between a given test and presently employed tools that have revealed valid knowledge assessment characteristics in the domain. Therefore, the TCS was selected as a potential tool for evaluating the concurrent validity of the SAFI concept map, which was prepared by the expert panel in this study.

Generally, the correlation level between the scores of two instruments shows whether or not each test is assessing certain similar abilities, and to what extent. Examining the difference between the obtained mean scores in two instruments helps show if the tests have comparable performance outcomes for examinees, and helps identify if there are differences in scores that might be significant to how factors correlate with each other (Anastazi & Urbina, 1997).

For this purpose, the required data was collected from TCS and SAFI concept map tests. Students have answered TCS and SAFI questions, respectively, during a 60 minutes exam. Then, the results for each student were obtained by comparing their answer sheets with the reference ones. In scoring the SAFI test, the answers of students need to be compared with the reference map prepared by the expert panel. If placed in the correct place, each concept would receive the positive value ‘1’ and no value if not. Thus, the TCS test has 35 values, while the SAFI test has 33 values in accordance with the number of empty places.

Results

The final scores obtained from the two tests for each student are illustrated in Figure 3. As the scores of the two tests have been measured on an interval scale, we have used Pearson’s Correlation Coefficient in order to calculate the correlation coefficient between TCS and SAFI in the current study, after examining the normality of the data (Table 1). The final results are shown in Table 2.

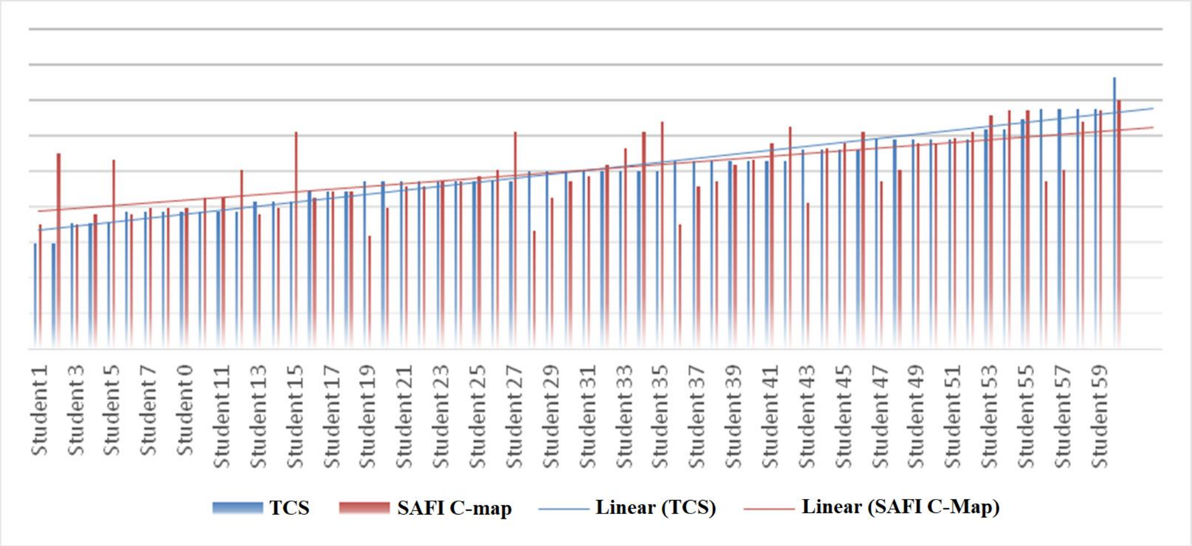

Figure 3. The final scores obtained from the two tests for each student

Table 1. Tests of Normality

	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
TCS	.089	60	.200	.980	60	.422
SAFI Cmap	.095	60	.200	.967	60	.109

Table 2. Pearson correlation

		TCS	SAFI C-map
TCS	Pearson Correlation	1	.611**
	Sig. (2-tailed)		.000
	N	60	60

** Correlation is significant at the 0.01 level (2-tailed)

Based on the data shown in Table 1, the scores of both concept map tests, i.e., TCS and SAFI, are normally distributed at the 5 % significant level ($p > .05$). Also, the correlation between TCS and SAFI concept map scores is 0.611 at the 0.01 level ($p < .01$). This suggests a moderate to a high positive correlation between the designed test (i.e., SAFI concept map) scores in thermodynamics and the standard test in the field (i.e., TCS).

Discussion and Conclusion

The current study's findings indicated that fill-in concept maps are a suitable instrument for measuring conceptual learning in students in thermodynamics. In fact, as these maps are simple to use and do not require instruction as to how to be used, they can be helpful in measuring the conceptual knowledge of students. Furthermore, it is recommended that due to their correlation with common conceptual knowledge tests, these tests can be used as supplementary or even predicting instruments. The results from the fill-in concept mapping tests can provide a good basis for measuring conceptual learning in students. Furthermore, by considering the obtained results from such tests, the misconceptions or misunderstandings of students can be identified, and before giving classroom or problem-solving tests, they can be provided with separate and remedial instruction.

Based on the findings of this study, also we can conclude that failing to get good grades or doing badly on science tests can be explained by a lack of proper understanding of the questions by students. As can be seen in Figure 3, students' numbers 2, 5, and 15 obtained very good scores on the concept mapping test, while they obtained very low scores on the TCS test which indicates these students did not have a proper understanding of thermodynamics. This inconsistency was explained by conducting an interview with each student whose descriptions threw light on the cause of this inconsistency. All of these students believed that their weakness on the TCS test was because they did not understand its questions. Indeed, while some of the students were able to understand this test's questions well, others had difficulty understanding them. The results from this part of the study are highly consistent with the results obtained from the test by TIMSS and PIRLS (2011) where they found a strong correlation between a student's ability to read and comprehend a given question and his/her ability to solve it (Martin & Mullis, 2013). Therefore, concept maps and particularly fill-in concept maps can be utilized as supplementary instruments for measuring students' conceptual understanding; and rather than relying only on classroom tests for analyzing a student's weaknesses, the results from these assessment tools can be used to form more comprehensive and appropriate judgments.

Limitations and suggestions for future research

One of the main limitations of this study is its 60-student statistical population. In fact, the larger the population of students, the more valid would be the calculated correlation coefficient between the scores. These 60 students were selected as the sample at hand through convenience sampling procedures, as conducting random sampling was not possible for the author. It is recommended that other studies be done for measuring the validity and reliability of fill-in concept mapping tests in other domains of science and with larger statistical populations. Moreover, this instrument can be used more often for measuring students' understanding of conceptual knowledge who are generally weak at literature and reading comprehension, and for assessing their competence in these circumstances. In this study, learners used pen and paper to fill in concept maps for conceptual learning in classrooms. However, enhancing students' conceptual understanding of difficult concepts can be more inspiring and effective for learners using advanced technology-enhanced learning environments (Farrokhnia et al., 2019; Taghizade, et al., 2020) compared with traditional settings. It would be interesting to explore how such advances in educational technologies can be applied for enhancing students' conceptual understanding. As explained before, concept maps are considered ill-structured tasks which require deep cognitive elaborations. Literature suggests that sharing individual concept maps with the peer fosters cognitive group awareness and thus their conceptual understanding (Farrokhnia et al., 2019). Peer feedback, peer interaction, and peer review strategies as promising active learning methods in classrooms (see Latifi & Noroozi, 2021; Noroozi & Hatami, 2019; Noroozi et al., 2016; Valero Haro et al., 2023) may have the potential to ease the cognitive demands of drawing concept maps for individual students. Future studies could explore how and under what conditions such peer learning activities could maximize the effects of drawing and analyzing concept maps for enhancing learners' conceptual understanding of difficult concepts such as in physics classrooms. Moreover, future studies can explore how using concept maps as an evaluation tool in high school science classes can be facilitated by implementing proper game elements (see Dehghanzadeh et al., 2023). Finally, due to the emergence of new artificial intelligence technologies such as ChatGPT and learning analytics (Banihashem et al., 2022; Banihashem et al., 2023; Farrokhnia et al., 2023; Noroozi et al., 2019), for future studies, we suggest taking steps forward and examining how these new technologies can facilitate the evaluation of students' conceptual learning of physics.

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