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ORIGINAL ARTICLE

Comparison of Learners’ Problem Solving Approaches and Success in Stoichiometry[#]

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[#] This study is part of second author’s master thesis.

ABSTRACT

The purpose of this study was to examine how learners’ problem-solving approaches and success changed from high school to graduate school. This case study included 15 participants who were purposefully selected regarding their grade levels. To examine the development, we asked three algorithmic questions and three problems, which were different from each other regarding the data given and the context provided by stoichiometry. The data were collected through a think aloud protocols. The participants were also requested to take notes, write equations, and make calculations. Deductive data analysis was conducted. Results showed that the participants were able to solve the algorithmic questions to some extent. However, all participants had some difficulty in solving the problems. Most of the participants did not use supportive approaches to solve the problems. Implications for chemistry teaching provided in light of the results.

KEY WORDS: problem solving; stoichiometry; case study; chemistry education; think aloud protocol

INTRODUCTION

In our daily lives, we are generally faced problems. Therefore, we have to spend sometime and energy to solve them (Pal and Poyen, 2017). Problems occur in different contexts and fields such as issues in engineering (Taktak and D’Ambrosio, 2017), an organization’s business (van Aken and Berends, 2018), and in education (Yuriev et al., 2017). Some of those problems may not have quick solutions; hence, we may need to do some research, consult experts, make a plan, implement the plan, and if necessary revise it (Hayes, 1981; Okes, 2019). Regarding the problems we face and their nature, Reid and Yang (2002) noted an interesting point. They view “life as a problem-solving process” (p. 83). At this point, we need to describe what a problem is. A real-life problem has unidentified parts (Brabeck and Wood, 1990), insufficient data, and unfamiliar context (Bennett, 2008). In other words, a problem has a gap “between where you are now and where you want to be” (Hayes 1981, p. xii).

Individuals should be prepared for life and its problems through education. Heyworth (1999) mentioned two basic goals of education, namely, providing knowledge for a specific domain (e.g., chemistry) and teaching how to solve problems. If life is a problem-solving process as Reid and Yang (2002) stated, and if educators aim to prepare individuals for life, then in school, problems should be utilized to train our learners. In light with the problem definition and its nature, problems used in schools should include some unknown parts that make learners think creatively for bringing the essential parts to cross the gap. However, teachers and instructors all around the world generally focus on more well-defined problems with only one specific (Bennett, 2004; Laurillard, 1997; Mackatiani, 2017; Okes, 2019; Reid and Yang, 2002; Yu et al., 2015), which is related to the first goal of education that is teaching knowledge for a specific subject domain as noted by Heyworth (1999). In other words, the second goal of education, teaching problem solving, is being ignored. In a recent book, van Aken and Berends (2018) mentioned theory-informed problem solving and stated that “[t]heory-informed does not, of course, mean copying theory into particular cases. Theory is, by definition generic and must always be contextualized for use in actual problem solving” (p. 7). If we relate van Aken and Berends’ (2018) theory-informed problem-solving construct with Heyworth’s (1999) point, we can state that teachers prefer to teach the theory (i.e., content knowledge) part, but they are reluctant to teach or model how to utilize the theory in solving problems. Regarding this situation, research in problem-solving literature has revealed that content knowledge, principles, and procedures are necessary for problem-solving; however, they are not enough to solve the problem and provide a working solution (Lester, 1994). To be a successful problem solver, learners need to both learn problem-solving heuristics (e.g., understanding a problem, making sensible assumptions, reasoning, and evaluating the solution) and practice them.

To conclude, in the light of the points summarized, learners from different levels of education receive content knowledge for different subjects each year; however, their problem-solving ability and use of problem-solving approaches are ignored or assumed to be developed through gaining more knowledge. In this study,

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we focused on, without the use of real problems in schools, how learners' problem-solving approaches develop, if any, from high school to graduate school. In other words, the purpose of the study was to collect evidence to answer the questions. First, to what extent does chemistry experience and knowledge (i.e., spending more years as a chemistry undergraduate and graduate student) support participants' problem-solving approaches. Second, how do their approaches for solving algorithmic questions (i.e., participants are familiar with) and authentic problems (i.e., participants are unfamiliar with) differ in stoichiometry topic.

LITERATURE REVIEW

What is Problem and Problem Solving?

In the literature, there are different definitions of what problem and problem-solving are, which means that there is a lack of consensus on those definitions (Greenbowe, 1983; Randles and Overton, 2015). Wood (2006) described the problem in an educational setting as "a situation where at present the answer or goal is not known. For the problems normally encountered in educational situations, the way to that goal is not known initially" (p. 98). Bennett's (2008) preferred to define what a problem is not, "a problem in chemistry is not an exercise that can be completed by working through a simple, familiar algorithm" (p. 60). Brabeck and Wood (1990) also discriminated ill- and well-defined problems. Ill-structured problems are "those for which one or more elements are unknown or not known with any degree of confidence" (p. 135), which can be viewed as problems whereas well-defined problems include all known elements. To conclude, a problem has at least some unknown parts and necessitates a deeper cognitive process to be solved (Randles and Overton, 2015). Use of scientific reasoning is the main difference between solving problems and algorithmic questions (Bennett, 2008; Randles and Overton, 2015).

The difference between the two is also related to the problem solver's experience (Bodner and Herron, 2002) and content knowledge (Greenbowe, 1983). A question may be a problem for someone who starts to learn chemistry while it may be a routine exercise for a chemistry teacher (Bodner and Herron, 2002). However, the situation may or may not change after taking some chemistry lessons (Greenbowe, 1983). Furthermore, it is also related to the number of times that you confront the item and whether you have solved it (Krulik and Rudnick, 1987, cited in Randles and Overton, 2015).

Similar to the lack of consensus on definitions, there is no consistency among the terms used. Regarding the variation in terminology used, Table 1.

In this paper, we used "problems" for the items with unfamiliar context, more than one solution method, and unidentified parts. In addition, we used "algorithmic question" for the items that have identified elements and can be solved only by the use of algorithms.

The Use of Problems and Algorithmic Questions in Educational Settings

Algorithmic questions and problems require different approaches to solve them, which sheds lights on implications for future research and goals of education (Churchman, 1971 cited in Brabeck and Wood, 1990). However, educational systems from around the world have generally depended on algorithmic questions (e.g., Malaysia – Surif et al., 2014, United Kingdom – Bennett, 2004, 2008, United States and Australia – Bennett, 2004, and Greece – Pappa and Tsaparlis, 2011). Questions asked in the exams and solved in teaching generally have one correct answer. To be successful in the exam, students need to remember the algorithm and the method needed to solve it (Wood, 2006). The algorithm plays a role in problem solving, but problem solving has other parts (e.g., making assumptions and bring in additional data) (Bennett, 2008). According to Brabeck and Wood (1990), the use of standardized tests, including algorithmic questions, hinders learners' development of problem-solving ability. Furthermore, it results in a distorted view of science in learners' mind (Wood, 2006). Learners learn to view science as "all is known" (Wood 2006, p. 98). In addition, learners do not have a chance to realize scientists' personal contribution to

Table 1: Examples of different terminology use

Researchers	Terminology for problems	Terminology for algorithmic questions
Greenbowe (1983)	Problems are "chemistry tasks that require the majority of individuals to use chemistry facts in conjunction with higher order reasoning and/or the application of algorithms in a multi-step procedure" (p. 9)	Exercise is "a task in which an individual recalls facts or skills and applies an algorithm (s) to obtain an answer to a task" (p. 8)
Wood (2006)	Open type problems have no correct answer but a best solution, or correct answer that can be reached with different ways. "Success in others may lie with economy of time, cost or scale" (p. 98)	Closed problems are one that have a correct answer
Bennett (2008)	Problems provide insufficient data and unfamiliar context. They may have more than one method to solve. In addition, outcome is not precise rather an estimate	Exercises are only application of algorithm
Brabeck and Wood (1990)	Ill-structured problems have some elements that are unidentified and have more than one correct/best solutio	Well-structured problems are asked with all elements are identified. They have only one correct answer

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science due to lack of idiosyncratic contributions to solution. Yet another disadvantage of overuse of algorithmic questions is ignorance of developing science process skills (e.g., data analysis and data seeking). On the contrary, teaching problem solving is useful regarding increasing motivation and retention, providing independence to the learner, and developing reflection skills (Bennett, 2008). Likewise, Nurrenbern and Pickering (1987) stated that to foster learners' conceptual understanding, problems should be used in science classes.

Review of Research Related to Problems and Problem-Solving Skills

First, some researchers focused on the different groups of participants' problem-solving skills and approach through a think aloud protocol. In an early attempt to examine the content and process variables on problem solving, Greenbowe (1983) studied 30 college chemistry students. Through a think aloud protocol, Greenbowe specifically focused on successful and unsuccessful participants' problem representation and conceptual understanding. Results revealed that successful ones were more able to use three levels of representations in chemistry (i.e., macroscopic, symbolic, and sub-microscopic levels) and to have a better representation of the problems. However, the less successful ones paid more attention to algorithms than the understanding of the problem. Likewise, Overton et al. (2013) studied 27 college chemistry students' approaches to problem-solving through a protocol. Results revealed that there were three groups of participants, namely, experts (i.e., using more scientific approaches to solve problems such as making approximations and assumptions), novices (i.e., using an unscientific approach including seeking algorithm and unable to understand the problem), and transition group that used both scientific and unscientific approaches. In another study, Randles and Overton (2015) compared expert and novice problem-solving approaches. All participants identified information needed, used algorithms, and identified and framed the problem. However, only the experts were able to develop a strategy and apply a scientific logical approach

Second, another group of researchers examined participants' performance on problems and algorithmic questions. Surif et al. (2014) compared 248 college students' performance on algorithmic, conceptual (i.e., questions included an unfamiliar chemical situation and conceptual understanding), and problems. Most of the participants solved algorithmic questions (96%), whereas only 14% of them could solve the problems. Regarding conceptual questions, 54% of them were successful. Similarly, Nurrenbern and Pickering (1987) compared general chemistry students' performance on algorithmic questions and problems. Results revealed that students were much more successful in solving algorithmic questions than solving problems. Their success in solving the former did not help them solve the latter, which meant that those questions assess different constructs. Likewise, Nakhleh et al. (1996) compared students' success in solving the two. These researchers stated that if the success gap was to be narrowed, problems must be solved in the courses.

Third, factors influencing participants' problem solving were examined. Lee et al. (2001) focused on cognitive variables, prior knowledge (PK), linkage (LG), and problem recognition skill (PRS). PK includes specific knowledge (SK) related to the problem and non-specific but relevant knowledge related to the subject. Second, LG contains concept relatedness (CR) and idea association (IA). Finally, PRS has problem translating skills (PTS) and prior problem solving experience. In the correlational study, Lee et al. studied the relationship between 9th -grade students' problem-solving skills of the "Mole" concept and the cognitive factors mentioned above. Except for the correlation between CR and problem-solving performance (PSP), other all correlations were moderate and statistically significant. In the multiple regression analysis, SK, CR, IA, and PTS significant y contributed to participants' overall PSP. Likewise, Kapa (2007) studied the influence of metacognitive support mechanisms (MSMs) on participants' ability to transfer from solving algorithmic questions to real problems. Different groups received MSMs at different phases of problem-solving (e.g., during each phase or at the conclusion of the problem solving), and control groups did not receive any support. Results showed that all experimental groups receiving MSMs were statistically more successful in the transfer from algorithmic questions to problems compared to the control group. In a recent study, Rodriguez et al. (2019) studied 40 learners taking a general chemistry course. Results revealed that when participants started with the use of data table, they could not find the final answer. In other words, they did not focus on or reason about what the data told them. Most of the participants who started the problem solving with conceptual reasoning could finish the process productively. In another study, Bennett (2006, cited in Bennett, 2008) compared university students' problem-solving skills regarding prior education, gender, and age. Results revealed that when participants focused on problems there was no significant difference in the performance of the groups with prior qualifications. Students with prior qualifications were more successful in solving algorithmic questions than others. Regarding gender, males had a tendency to get into the problem faster than females did. However, there was no difference in overall performance between males and females.

Finally, in some studies, exam questions were examined. Bennett (2006, cited in Bennett, 2008) analyzed chemistry exam questions asked in English colleges. Results showed that about 90% of the exam questions were algorithm type. Bennett (2004) analyzed the exam questions asked at colleges from the United Kingdom (i.e., 22 institutions), United States of America (i.e., six institutions), and Australia (i.e., four institutions). In total, they analyzed 432 exam questions, 94.7% of which was algorithmic type.

Theoretical Framework

In the related literature, there have been some frameworks for the problem-solving process (e.g., Runco and Chand, 1995). However, some of them are linear and not dynamic (Basadur et al., 2014). Due to the dynamic and iterative nature of the problem-solving process, the Creative Problem Solving Profil (CPSP) framework proposed by Basadur and Gelade (2006) was used in this study (Figure 1).

In the CPSP framework, Basadur et al. stated that the process includes four stages, namely, generating, conceptualizing, optimizing, and implementing. To visualize the model, they divided a circle into four quadrants; one of each represents a stage of CPSP. The iterative nature of the process is represented by the use of arrows surrounded the quadrants.

In the generating stage, the person who is supposed to solve a problem is faced with the problem and generates information about it. The problem and its details are identified. In other words, generating is a preliminary stage (Basadur and Gelade, 2006). Second, in the conceptualizing stage, "a problem or opportunity identified in the previous stage is analyzed to create a comprehensive conceptualization or model of the problem domain" (Basadur et al. 2014, p. 83). In other words, the problem is analyzed and understood. The formulation made in this stage is utilized in producing the solution/s process. Third, in the optimization stage, the problem solver optimizes the conceptualization made in the previous stage by taking limitations and possible struggles into account. Then, in the implementation stage, the solution is applied to the problem, and observations are made to evaluate the solution created. If the solution is successful the process ends, if not modifications are made, which reflect the dynamic nature of the process (Figure 1). Although they go through the same stages, different individuals implement different cognitive strategies, which results in diverse problem-solving styles (Basadur et al., 2014). Related to the varying problem-solving approaches, Overton et al. (2013) provided a useful framework that elaborates strategies implemented by learners during problem-solving process (i.e., details of this framework are given in methodology part of the paper).

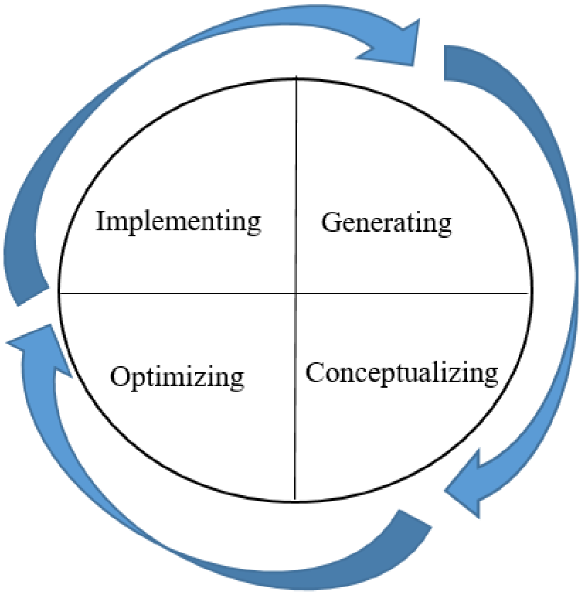

Figure 1: The creative problem-solving profile framework proposed by Basadur and Gelade (2006)

Significance of the Study

"Currently, there is insufficient known about the approaches chemistry students use to answer open-ended problems, with most research focusing on algorithmic problem-solving perspectives" (Randles and Overton, 2015, p. 4). Moreover, "much of the published evidence in the area of problem solving in chemistry has focused how students tackle algorithmic or structured problems or on what factors affect their performance in more open-ended problems" (Overton et al., 2013, p. 469). Hence, we do not know much about how students from high school to graduate level approach problems and algorithmic questions. Problem-solving tasks "require the application of knowledge and principles to new situations…. Knowledge without the ability to apply it is rightly seen as a very poor commodity" (Laurillard, 1996, p. 126). From high school to the graduate level, students learn new knowledge. However, the increase in the grade level does not mean enrichment in problem-solving skills. The courses offered to students should include real problems and integrate problem-solving skills (Laurillard, 1997; Yu et al., 2015).

In Turkey, our education system (i.e., due to high stake exams for entrance to successful high schools in the 8th grade and for universities in the 12th grade) is dominated by algorithmic questions asked in multiple-choice format. Hence, not all of the participants are familiar with problems. The exam dominated system and overuse of multiple-choice questions are also seen in other countries. These issues have been existed in many countries around the world such as China, Kenya, Taiwan, and the US (Kirkpatrick and Zang, 2011; Mackatiani, 2017; Morgan, 2016; Yu et al., 2017).

In light of the points presented above, our study investigated to what extent does chemistry experience (i.e., spending more years as chemistry undergraduate and graduate student) support participants' problem-solving approaches. In addition, the research sought to identify to what extent participants' approaches and success development for solving problems and algorithmic questions are related to the participants' educational level.

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METHODOLOGY

Type of the Study and the Participants

This study was a qualitative multi-case study (Patton, 2002). Cases can be an event, a subject, or setting (Merriam, 1998). Cases were learners from different levels of education. Table 2 shows the details of the participants.

In terms of participants, we utilized a convenient sampling method (Fraenkel and Wallen, 2006). In other words, we reached participants who were easily available. We explained our purpose and invited them to participate in our research. On a voluntary basis, we selected three participants (i.e., who were available within 2 or 3 days after invitation to participate in an interview protocol) from each group for the sake of easiness in interviewing, transcription, analysis, and reporting of the data. Because this was qualitative research in nature, we were not seeking generalization of the results. Therefore, we could manage 15 participants. Moreover, we paid specific attention to learners' understanding in stoichiometry and chemical calculations. To check their familiarity with problems, we took necessary information about how their teachers and instructors taught chemistry. We also asked participants whether they were familiar with authentic problems. Regarding this point, we also observed that no participants had been faced with authentic problems before. When they read the problems, they were initially shocked, had to read the problem again to try to understand and analyze the problem, which revealed their unfamiliarity to us. We also selected high school students from the 11th grade because; they learned those topics in the 10th grade. Furthermore, we did not select freshmen due to the fact that the data were collected in the fall semester through which they may not have yet covered the topic in General Chemistry I. All the undergraduate students took General Chemistry I and II at least 2 years previously. The three graduate students had graduated from a 4-year chemistry program and were enrolled in graduate school. They had all taken graduate courses and were completing their master thesis at the time of data collection.

Data Collection

The data were collected through think aloud protocol through which the participants were asked to verbalize their thoughts and actions while doing something (e.g., solving a problem) (Patton, 2002). The aim was "to elicit the inner thoughts or cognitive processes that illuminate what is going on in a person's head during the performance of a task" (Patton, 2002, p. 385).

All participants were requested to take notes for calculations or reaction. All think aloud sessions were audio-recorded and transcribed verbatim. The records took between 30 and 45 min. At the beginning of each protocol, we talked to the participants and informed them about the process (i.e., we need to hear what they think while solving the items). In addition, we stated that there may be no single answer to the questions asked. They were allowed to use a simple calculator. As researchers, we both conducted the first four interviews together to train the second author who conducted the rest of the interviews. Researchers paid specific attention not to interrupt or direct them. Records and their verbatim transcripts, and documents that participants took notes on were the data sources for the study.

We asked three problems and three algorithmic questions from stoichiometry. An example of a problem is:

We modified it from Overton e al. (2013).

An example of an algorithmic question asked is:

The problem and the algorithmic question included very similar reactions and calculations. However, in addition to reaction knowledge, problems also necessitated the use of problem-solving approaches such as conceptualizing the problem, estimations, approximations, and reasoning. During the protocol, first, we asked the problem, and then we asked its related algorithmic question to prevent participants from getting bored or becoming disappointed with unfamiliar problems asked sequentially. Therefore, in the result section, problems numbers are 1, 3, and 5 rather than 1, 2, and 3.

Analytical Framework and Data Analysis

In this study, the framework developed by Overton et al. (2013) was utilized (Table 3).

The (+) sign of the codes shows the ability of doing the code and (-) sign shows the inability to do it. Overton et al. (2013) grouped the approaches into two groups, namely, supportive approaches that may lead to a reasonable solution (i.e., E+, P+, L+, A+, and EV that are the rows painted in gray in Table 3) and unsupportive ones that are unlikely to result in a reasonable solution (i.e., E-, L-, P-, A-, AL, and CO). In the tables given in the results part, we separated the supportive and unsupportive ones by the use of dashed line. Finally, the

Table 2: Details about the participants

Institutions	Number of participants from each sub-group	Details	Numbers given to participants
High school	Three students	11th grade (two females and one male student)	1–3
Undergraduate students	Nine students (three students for each grade)	Three sophomores (two females and 1 male) Three juniors (two males and one female) Three seniors (three females)	4–12
Graduate students	Three students	From chemistry department and studying for a master degree in pure chemistry (two males and one female)	13–15

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Table 3: Categories, codes, and example and/or explanations

Category	Code	Example and/or explanation for the code
Makes estimations, approximations generates data	E+	Participant makes estimations for instance about how many times an adult breaths per minute
Unable to make estimations, approximations or generate data	E-	Participant who is not able to use the details given to make estimations
Understands the problem, what needs to know or do	P+	Participant realizes that s/he needs to number of passengers to calculate the mass of KO_2 for the fligh
Cannot get started, cannot identify what needs to know or do	P-	Participants who do not know where to start, read the problem many times
Logical approach and reasoning	L+	Participants may suggest a logical different way that is very unique to his/her for a solution to the problem
Not logical, gaps in reasoning	L-	Participants who try to provide a way to solve the problem but provide illogical ones
Makes sensible assumptions	A+	Participants assume that all adults breath 15–20 times/min
Guesses	A-	Participants may think that the reaction takes 1 h (For fight problem given above)
Evaluates answer, aware of limitations	EV	Participant evaluate his/her answer and realizes the limitations regarding assumptions done
Seeks the algorithmic approach	AL	Focuses on calculations rather than understanding
Distracted by the context of problem	CO	Participant may state that the question is so long and s/he gets lost
Lack of knowledge a barrier	KN	Participant who is not able to use reactions to do anything with the items

use of supportive approaches was shown by shading the cells with black. For unsupportive ones, the cells in the approaches table were shaded with gray.

In addition to those categories, we also realized that some participants had some misconceptions, which required us to add an M code to our list. Having misconceptions are very different from a lack of knowledge (i.e., KN). Hence, we added that category into the framework.

The CPSP framework proposed by Basadur and Gelade (2006) and the approaches used for problem-solving framework developed by Overton et al. (2013) can be related to each other. As Basadur and Gelade (2006) stated, individuals, use different approaches and strategies in each stage of CPSP framework. Those strategies were revealed by Overton et al. (2013). Figure 2 shows that the approaches can possibly be utilized in each stage of CPSP.

The strategies revealed by Overton et al. (2013) can either be supportive (e.g., P+) or unsupportive. Therefore, participants may use supportive ones that may result in a successful solution or use unsupportive ones that will not result in a reasonable solution.

Regarding the success in solving the algorithmic questions and problems, we, first prepared a key showing the feasible solutions. Then, we examined 25% (i.e., a random number we selected) of the data collected and realized that we had three types of answers, namely, wrong answers (i.e., - sign was used), partially correct ones (i.e., P was used), and correct ones (i.e., + was used to show in tables in the result part). Finally, we decided to give zero point to wrong ones, a half-point to partially correct ones, and one point to correct ones. This data analysis was applied to the rest of the data. The first author coded the rest of the data.

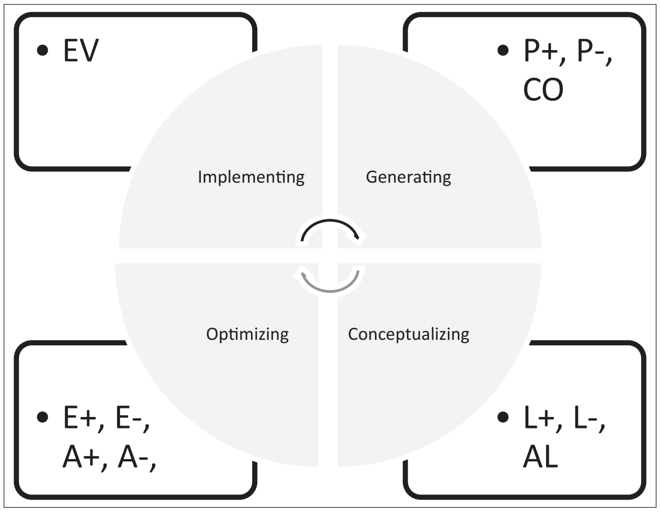

Figure 2: Strategies that can be used in creative problem solving profile framework

To identify the approaches used and determine the success of each participant, transcripts of the think aloud sessions were coded by the use of codes. Data coding showed that a participant might use more than one approach through the protocol. Both researchers coded about 25% of the data (i.e., transcript and notes of four participants from different levels) independently. Then, they compared and contrasted the data coding. The inter-rater reliability was calculated as 0.88 for approaches and 0.95 for success categories (Miles and Huberman, 1994). The researchers resolved any inconsistencies. Then, the first author coded the rest of the data.

In this study, to ensure credibility, data triangulation (i.e., use of think aloud transcripts and notes taken by participants during think aloud sessions), and methodology triangulation (i.e., use of in-depth analysis, enumerative approach, and constant-comparative method), and member check were utilized (Patton, 2002).

RESULTS

Approaches Used for Solving Problem 1

In this question, participants were asked to calculate how much reactant was necessary to produce HARIBO in the conditions given. The problem was modified from Fach et al. (2007). Table 4 shows the approaches utilized. We shaded supportive approaches with black whereas unsupportive approaches with gray. Moreover, a participant may use an approach more than once. Some of them either tried to solve the problem more than once or used the approach more than once. However, the total number of participants used column states the number of participants utilizing the approach rather than the number of times that the approach was used.

Regarding supportive approaches (e.g., P+, E+), five participants out of the 15 understood what needed to be done to solve it (P+) (Table 4). However, none of them made estimations (E+) or used reasoning (L+). Regarding unsupportive approaches, all participants used at least one of them. The most often used one was algorithmic (AL). Except for one participant (#13), all others adopted an algorithmic approach. Similarly, participants from high school to graduate level had gaps in their reasoning (L-) while solving the problem. An interesting result was related to the distraction by the context of the problem (CO). Nine participants from different levels stated the distraction explicitly. For instance, the 5th participant stated:

> *I could not understand what I was asked to do. The machine sounds the alarm… I am not able to solve this.… I do not understand. For example, I just focus on reaction between NH_4Cl, NH_3 or HCl…*

Similarly, the 6th participant said that the context given in the problem was pointless. He likened it to just "beating around the bush."

Finally, the 9th participant's (a junior student) transcription showed that she had a misconception about the use of mole ratio. She used mole ratio as a mass ratio.

Regarding the number of participants who solved the problem, Table 5 summarizes the results.

As Table 5 shows, none of the high school students solved the first problem correctly. Four of undergraduate students and a graduate student also could not solve the problem. Regarding the level of participants from high school to graduate level, an increase, at least to some extent, in the number of participants who solved the problem correctly was observed. However, one graduate student and four undergraduates could not solve it.

Results for Problem 3

In this problem, participants were required to calculate the mass of KO_2 needed to provide breathable air in an aircraft recirculation cells for an 11-h Istanbul-New York flight by the use of the two reactions given. To solve it, participants needed to make some estimations (E+) to generate data, for instance, they could have estimated how many breaths we take in a minute and how much CO_2 we produce in 1 min. In addition, they needed to assume some other details (e.g., number of

Table 4: Approaches used while solving problem 1

Approaches	Participants															Total # of participants used the approach
	High school students			Sophomores			Juniors			Seniors			Graduate students			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
E+																0
L+																0
P+						1	1				1	1		1		5
A+																0
EV																0
E-																0
L-	3	1		1				1	1	2			2		1	8
P-		1	1	1	3	1		1	2	2					1	9
A-										1						1
AL	1	1	1	1	3	3	1	1	1	1	1	1		1	1	14
CO	1	1		1	1	1	1	1					1	1		9
KN					1											1
M									1							1

Table 5: Participants' success results regarding problem 1

Participants	High school students			Sophomores			Juniors			Seniors			Graduate students		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Result	-	P	-	-	P	+	+	-	-	-	+	+	P	+	-

(-) means wrong solution, (P) means partial solution, and (+) means correct solution

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passengers). Table 6 presents the approaches adopted by the participants for solving the problem.

In the solution of this problem, only those participants from undergraduate and graduate levels adopted all of the supportive approaches except evaluating answer (EV). For instance, the 6th participant assumed about the duration of breath to calculate how many breathes a person took during the journey (E+). He also understood that he needed to know how many grams of CO_2 were produced by a person during respiration (P+). Likewise, the 12th participant also made estimation about the number of passengers in the aircraft (E+). Only one graduate student made estimations about the number of breaths in a minute. None of the high school students used an approach that could have led to a feasible solution to the problem (Table 6). Regarding the unsupportive approaches, the number of participants using them was high. Furthermore, most of the unsupportive ones were utilized at least one participant. Twelve participants could not understand what they needed to do to solve the problem (P-). Nine of them focused on the algorithm (AL) and tried to calculate something related to the problem, whereas six participants had wrong guesses (A-). For instance, they thought that the reactions given took 1 h to complete, which is irrelevant. Finally, the 6th participant thought that those two reactions were the steps of a net reaction (KN), which is incorrect. She tried to convert the reaction to cancel the products and reactants that existed in both reactions. Table 7 shows the number of participants who solved the problem.

As Table 7 shows, none of the participants solved the problem. Only two undergraduate students partially solved it through making estimations and reasoning (E+ and L+). The number of participants solving the problem correctly did not show a straight increase from high school to graduate one.

Results for Problem 5

The problem was about antacid tablets, including calcium carbonate, to treat the disease related to the increase in acidity of the stomach. The participants were asked to calculate how many grams of calcium carbonate that one antacid tablet should contain. The problem was modified from Fach et al. (2007). Results are presented in Table 8.

Similar to the previous problem, none of the high school students adopted a supportive approach to solve the problem whereas four undergraduate and all three graduate students adopted an approach (i.e., understanding the problem and what they need to know or do) (Table 8). Only one undergraduate student (the 8th one) used a logical approach (L+). Moreover, none of the participants evaluated their answer. Regarding unsupportive approaches, 13 participants paid more attention to algorithms (AL). Six participants (three high school students, two undergraduate, and one graduate student) could not write and balance the equation between calcium carbonate and hydrochloric acid, although the reactants and products were given. Moreover, five participants could not understand the problem at all (P-) and another five showed a gap in their reasoning (L-). To illustrate:

> *A single dose of an antacid is to be chosen in a way that it will react with two grams of hydrochloric acid. One mole of HCl is 36.5 gram. Then, how many doses are necessary? 18.25 moles are necessary, however, in the reaction; the number of moles of HCl is two. So, it has to be double.*

Table 6: Approaches used for while solving problem 3

Approaches	Participants															Total # of participants used the approach
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
E+						2						1			1	3
L+								1								1
P+						1	1	1				1				4
A+						1										1
EV																0
E-	1			1	1		2	1	1	1			1		1	9
L-			1			1	2			1	1					5
P-	1	1	1	2	1	1	2		2	2			2	4	2	12
A-		1	1			1				1	1			1		6
AL	1		1	1		1			1	1		1	1	1		9
CO		1											1		1	3
KN						1										1
M																

Table 7: Participants' results regarding problem 3

Participants	High school students			Sophomores			Juniors			Seniors			Graduate students		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Result	-	-	-	-	-	P	-	-	-	-	-	P	-	-	-

> *I mean 18.25 x2= 36.5 if I think in that way 18.25 doses of calcium carbonate are necessary.* (11th participant)

Finally, one junior student (the 9th participant) had a misconception about the use of mole ratio. She used mole ratio as a mass ratio. Table 9 shows the number of participants who solved the problem.

In total, seven participants solved the problem correctly. None of the high school students solved the problem. Regarding the level of participants, an increase, at least to some extent, in the number of participants who solved the problem correctly was observed at undergraduate and graduate levels. However, still, four undergraduate and one graduate could not solve the problem.

Results for Comparisons of the Participants' Success in Solving Problems and Algorithmic Questions

Results of the analysis for comparisons are presented in Table 10.

Items 1–2, 3–4, and 5–6 are somehow similar regarding the reactions types and calculations needed to be done. However, the problems (items 1, 3, and 5) included insufficient data or unfamiliar context. Moreover, they could be solved through different ways. Contrary, the algorithmic questions (items 2, 4, and 6) did not have any context. All necessary data and the reactions were given. There were three possible comparisons per participant due to the fact that we asked three sets of algorithmic questions and problems (therefore, 15 × 3 = 45 total comparisons). Twenty out of the 45 comparisons (about 45%, shaded in Table 10). Participants either could not solve the problem but solved the conjugate algorithmic question or partially solved the problem but solved the algorithmic one.

A final result (Table 10) highlights that none of the participants could solve all of the items asked. In the total points received, there was no consistent tendency between participants from high school and graduate school. Some of the undergraduate students got higher scores than graduate students. However, it could be stated that undergraduate and graduate students outperformed high school students.

DISCUSSION AND CONCLUSION

In this study, we compared and contrasted the participants' problem-solving approaches and success in solving algorithmic questions and problems. Results revealed that participants engaged in more unsupportive approaches than supportive ones while solving problems. When we looked at the groups separately, none of the high school students were able to make estimations, generate data, understand the problem, or make assumptions. In the undergraduate group, grade level was not a factor determining the use of approaches. For example, some participants (e.g., the 6th, 7th, 8th, and 12th participants) adopted supportive approaches for 6, 2, 3, and 4 times, respectively (Tables 4, 6 and 8). Hence, we did not see an increase in the number of times using them through grades. Similarly, graduate students (the 13th, 14th, and 15th participants) also engaged in supportive approaches for 1, 2, and 2 times, respectively. To conclude, a steady increase was not observed in the use of the scientific and supportive approach for solving problems when we compared the levels. The differences observed are more likely to be idiosyncratic because it is highly related to the problem solver's experience (Bodner and Herron, 2002) and content knowledge (Greenbowe, 1983). An undergraduate participant (e.g., the 6th participant) may

Table 8: Approaches used for while solving the antacid problem

Approaches	Participants															Total # of participants used
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
E+																0
L+								1								1
P+					1	1				1		1	1	1	1	7
A+																0
EV																0
E-																0
L-	1	1	1	1							1					5
P-	2	1		1				1			1					5
A-																0
AL	1	2	2	1	1	1	1	1		1	1	1		1	1	13
CO				1	1		1	1						1		5
KN	1	1	3	2					1				1			6
M									1							1

Table 9: Participants' results regarding problem 5

Participants	High school students			Sophomores			Juniors			Seniors			Graduate students		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Result	-	-	-	-	+	+	+	-	-	+	-	+	-	+	+

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Table 10: Results for comparisons of participants' success in solving problems and algorithmic questions

Items	High school students			Sophomores			Juniors			Seniors			Graduate students		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	-	P	-	-	P	+	+	-	-	-	+	+	P	+	-
2	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+
3	-	-	-	-	-	P	-	-	-	-	-	P	-	-	-
4	-	-	-	-	+	+	+	+	-	-	+	P	P	+	+
5	-	-	-	-	+	+	+	-	-	+	-	+	-	+	+
6	+	-	+	-	+	+	+	+	+	+	+	+	+	+	+
Total point got	1	0.5	1	0	4.5	5.5	5	3	2	3	4	5	3	5	4

(-) means wrong solution (i.e., o point), (P) means partial solution (i.e., 0.5 point), and (+) means correct solution (i.e., 1 point per item)

utilize more scientific approaches than graduate ones (e.g., the 13th or 14th participants), or a sophomore student (e.g., the 6th participant) engage in more supportive ones than a junior student (e.g., the 12th participant).

Another point is that some of the participants were not able to determine what they needed to know to solve the problem. Especially high school students had this problem as well as some undergraduate and graduate students. Similar results were observed in the undergraduate students' problem solving in Randles and Overton's (2015) study. However, a significant difference was that their expert participants were able to identify what they needed and used it for solving the problem successfully.

Related to the comparisons groups, Overton et al. (2013) grouped their participants regarding the approaches that they utilized during problem solving. They had three groups: "Experts problem solvers" who adopted only supportive approaches, "novice problem solvers" who utilized only unsupportive approaches and "transitional group" who used both types of strategies. However, Randles and Overton (2015) stated that participants could not be categorized as clearly as Overton et al. (2013) did because participants used both supportive and unsupportive approaches. Likewise, in our study, except for the high school students, some of the undergraduate and graduate participants (e.g., the 6th and 14th participants) used both approaches for solving the problems for many times, which can be categorized as a transitional group. However, grouping participants into those groups are complicated because some participants (e.g., the 1st, 11th, and 13th participants) engaged in supportive approaches only once through the whole of the protocol. These participants used unsupportive ones most of the time. Therefore, we argue that using those approaches may not be the only indicator of being an expert or novice. How many times of use would be necessary to be accurate in grouping? When we look at their numerical scores, we see a low success percentage for all of them. Are they categorized into novice or transitional group? We suggest that they should be in the novice group due to their dominance of unsupportive approaches adopted in their protocol and also their low numerical scores. This suggestion worked for the participants who categorized in the transitional group. When we looked at Tables 4, 6 and 8, we see that the 6th, 7th, 8th, and 15th participants utilized supportive approaches many times for solving different problems. In addition, they got high scores overall (Table 10). Finally, participants from high school were not able to use any supportive approaches. Furthermore, none of them was able to solve the problems. Regarding the groups occurring, Overton et al. (2013) stated "[t]he three types of problem solvers did not correlate with age or year of study, so this transition, if indeed it is a transition, must be related to intellectual development, practice or cognitive factors" (p. 474). Likewise, our results clearly support this statement. Both high school and some undergraduate students (i.e., the 4th, 5th, and 9th participants) can be categorized into the same group that of novice problem solvers. Although there was a big difference between their age, practice, and development, they were still in the same group.

Regarding the types of approaches used by different groups, first, we observed that all participants predominantly focused on the algorithmic approach for solving the problems. Similarly, all participants both from expert and novice groups used the algorithmic process in Randle and Overton (2015). On the contrary, in Overton et al. (2013), participants from the expert group did not use algorithmic approach whereas novices and transitional problem solvers used it. Second, none of the participants in the study evaluated their solutions. In the Randles and Overton's study (2015) experts evaluated their solution during and at the end of the process whereas undergraduate students engaged in an evaluation of the solution at the end. In addition, experts engaged in more evaluation than undergraduate students did. In other words, evaluating the process of solution and the end product are more likely to be related to being an expert. In our study, we concluded that we did not have expert problem solver in the study group; therefore, this result is consistent with our previous categorization. Yet another point needing attention is "the distraction by the context of the problem." Participants from three levels complained about the context of the problem and stated that they found some information useless. These complaints are highly related to their previous experiences with algorithmic questions asked in the textbooks (Pappa and Tsaparlis, 2011) and by teachers (Bennett, 2004, 2008; Nakiboglu and Yildirir, 2011).

Regarding the success comparisons for solving problems and algorithmic questions, (i.e., shaded in Table 10), about 45%

comparisons showed that participants either could not solve the problem but solved the conjugate algorithmic question or they partially solved the problem but solved the algorithmic one. The result is also related to the previous experience of participants who solved algorithmic questions with no context but with all necessary data. When we think that the high school students learned stoichiometry almost 1½ year before this study, and others have had at least 4–8 years' experience with stoichiometry, the results are disappointing for chemistry education. As Greenbowe (1983) stated, a difficult problem would either be an ordinary exercise or still be a difficult problem after some experience. However, the situation may or may not change after taking some chemistry lessons. Similar results were revealed by Nakhleh, et al. (1996), Nurrenbern and Pickering (1987), and Surif et al. (2014). In their studies, participants were much more successful in solving algorithmic ones than they were in solving conceptual ones. As Nurrenbern and Pickering (1987) stated, problems and algorithmic questions assess different contracts (e.g., understanding, transfer of knowledge to new context vs. algorithmic calculations, and recall of knowledge). Hence, high success in solving algorithmic ones does not ensure success in problem solving. Our results and other studies support Nurrenbern and Pickering's (1987) point out that we, as chemistry educators need to think to what extent, we prepare our students as problem solvers.

Finally, when we looked at the use of approaches regarding the stages of CPSP framework (i.e., generating, conceptualizing, optimizing, and implementing) (Basadur and Gelade, 2006), results revealed that almost all these participants had difficulty in all four stages. To be more specific, we can state that a logical approach and reasoning (L+) was missing in the conceptualizing stage. In the optimizing stage, the participants had difficulty in making estimations, approximations, generating data (E+), and making sensible assumptions (A+). In the last stage, none of the participants could evaluate the solution and focus on the limitations of the solution (EV).

To conclude, receiving more and deeper knowledge about a topic (i.e., stoichiometry), and more experience does not result in successful problem solving and use of supportive strategies. Our results revealed that learners needed to observe how experts solve problems with missing data and parts (Mackatiani, 2017; Yu et al., 2015), need to learn problem-solving strategies (e.g., how to make reasoning about the problem) (Morgan, 2016; Rodriguez et al., 2019), and practice them in problem-solving process (Yu et al., 2015). On the other hand, for solving algorithmic questions, participants with necessary stoichiometry knowledge could solve them, which show that problems and algorithmic questions are very different constructs that they require different strategies to be solved. Teachers' focusing only on providing knowledge and emphasizing only algorithmic questions mean ignoring education's major aim of preparing learners for a life that must deal with problems.

IMPLICATIONS

Use of problems and algorithmic questions in textbooks, exams, or in the class serve to assess different constructs (Nurrenbern and Pickering, 1987). Therefore, teachers, academicians, and textbook writers should include more problems into their teaching and textbooks to narrow the gap between success gap solving problems and algorithmic questions (Mackatiani, 2017; Morgan, 2016; Nakhleh et al., 1996). The inclusion of the problems would be useful for developing a more realistic view of science in students' mind (Wood, 2006). With the unidentified elements, multi-step procedure, and more than one possible solution, problems are more likely to show that scientists do not have all the data necessary, rarely do they have all the details about the problem that they are dealing with. It is also useful for developing science process skills (e.g., data analysis).

In light of the results, high school and undergraduate students need more practice, time, and support to develop a more scientific view and learn supportive approaches for solving problems. As in Kapa's (2007) treatment study, MSMs should be offered to students who have difficulty in solving problems. Moreover, chemistry teachers and instructors should be a role model of reasoning, use of the context, making estimations, and evaluating answers while they are solving problems in the classroom. Similarly, different approaches and supports such as "The Goldilocks Help workflow" that provides a step-by-step process, namely, introduction of the problem, encourage learners for reasoning about the problem and its details, and support learners for having metacognition and self-regulation for problem solving, should be implemented (Yuriev et al., 2017). Another good practice would be peer instruction (Gok and Gok, 2016).

Regarding what should be done in the classroom, Yu et al. (2015) suggested to implement a three-step problem-solving approach including watching detective films, context simulation to help learners conceptualize the problem, and project design. Yu et al. (2015) revealed that participant middle school students develop their problem-solving process through training including three-step approach, especially support provided with context simulation was useful for developing learners' understanding of the problem. If learners have this type of support in the early stages of education, they may develop their conceptualizing ability and may need less support in the later grades. In addition, Yu et al. (2015) stated that providing a chance to failure in the problem-solving process is important for preparing them for life. In this respect, project design should be included. In the project design, learners have a chance to experience failure. They come to realize that solutions may not work so their solutions should be modified. Another implication may be the teachers' modeling of use of effective problem-solving approaches. Under teachers' guidance, problems can be solved and the solution can be evaluated (Özsoy & Ataman, 2017). As Randle and Overton (2015) stated, expert problem solvers are able to develop a

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strategy and apply a logical approach when they face with a problem. Those types of strategies used by experts should be implemented by teachers in class while solving a problem.

Limitations of the Study

This study was carried out with a small sample selected on purpose (i.e., regarding grade level) but conveniently. Therefore, the results of the study cannot be generalized to other groups. Moreover, the participants have been educated in a test and exam dominated system. Therefore, different results may be received from participants with less experience in tests. Furthermore, we asked only three problems, which may not be enough to investigate fully about these participants' problem-solving approaches and success. Finally, the use of think aloud protocol may cause some stress on participants.

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