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The Effect of Heuristics on the Reasoning of the Pre-Service Science Teachers on the Topic of Melting and Boiling Point

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Abstract

The purpose of this study was to explore the effects of the heuristics on the reasoning processes of pre-service science teachers on the topic of melting and boiling point using the ten heuristic model proposed by Talanquer. In this phenomenographic study carried out in the spring semester of the 2018–2019 academic year, interviews were conducted with 30 teacher candidates enrolled in the Science Teaching Program of Firat University Faculty of Education. Participants were asked to answer three different questions during the interviews. These questions were about the ranking of some compounds according to their melting or boiling points. Six different answer patterns for each question were obtained from the answers. The findings of this study showed that students generally used shortcut strategies instead of analytical/scientific reasoning, as all ten heuristics affected participants' reasoning. This study also revealed that although not included in the model proposed by Talanquer, periodic trends heuristic also influenced participants' reasoning about the melting and boiling point.

Keywords: Chemistry education; cognitive constraints; heuristics; melting and boiling point; reasoning; science education.

1. Introduction

In order to make predictions about the melting and boiling points of compounds, it is necessary to know well the interactions between particles and the molecular structure-property relationships. The structure-property relationships and the effects of interactions between particles on melting and boiling points have an important place in chemistry curricula. Because of this importance, there are many studies in the literature on students' understanding of the structure-property relationships and the effects of interactions between particles on melting and boiling points.[1–6] In these studies, students' understanding of melting and boiling phenomena was examined from different dimensions. The findings of these studies showed that students often had difficulties in understanding interactions between particles and structure-property relationships, and could not make accurate predictions or rankings about the melting and boiling points of compounds due to these difficulties. It was also reported in the findings of these studies that students generally relied on shortcut strategies instead of analytical/scientific reasoning, students had various misconceptions regarding the mentioned subjects, and students' reasoning, judgment and decision-making processes about melting points and boiling points were generally flawed.

In order to understand the causes of students' learning difficulties, students' reasoning and cognitive constraints that constrain scientific reasoning should be explored in detail. Reasoning is the act of thinking about something logically. Cognitive constraints are cognitive factors/elements that restrict individuals' analytical/scientific reasoning.[7–11] The best known of cognitive elements include core knowledge,[12] intuitive rules,[13] implicit assumptions,[14] conceptual sources,[15] basic hypotheses and ontological beliefs,[16] inductive constraints,[17] primitive phenomenologies[18] and heuristics.[19]

Heuristics are related to the "dual process" theory, which was developed to explain the judgment and decision-making processes of individuals. According to the dual process theory, two different cognitive systems called System 1 and System 2 are used when individuals make judgments or decisions. System 1 includes cognitive processes that progress rapidly, automatically and unconsciously, while System 2 includes cognitive processes that progress slowly, prudently and consciously.[20–23] Using previous knowledge and beliefs, System 1 processes are contextual, relational, holistic, automatic, and working memory-independent processes. Slow and sequential System 2 processes are the processes that provide rule-based, analytical, abstract reasoning and use working memory.[23–26] No special effort is required to trigger System 1 processes.[23,27] System 1 processes are related to the intuitive reasoning of individuals. System 2 processes require special cognitive effort and conscious interventions.[27] The System 1 processes described in detail above are short-path reasoning strategies and are called heuristics.[20,23,28–30] In conditions where knowledge or motivation is lacking or when time is limited, heuristics play an extremely active role.[23,31,32] Heuristics enable decision-making in a short time without cognitive effort since they evaluate fewer factors and use fewer cues in the reasoning and judgment processes.[33] However, heuristics are responsible for various cognitive biases observed in the reasoning processes.[10,23]

There are many studies in the literature exploring the effects of heuristics on the judgment and decision-making processes of individuals' daily lives.[23,30,34] Research groups in different disciplines such as cognitive psychology, psychology, behavioral finance, and behavioral sciences generally carried out these studies. The heuristics identified in these studies were generally named with different names specific to the studied field. The heuristics identified in these studies and named with different names actually use similar cognitive processes.[23,30,31] For this reason, some scientists have started to study on collecting the heuristics that progress with the similar mechanism under a general heading. For example, Morewedge and Kahneman grouped the heuristics, which frequently affect the judgment and decision-making processes related to the daily lives of individuals, under three headings. These heuristics are representativeness, availability and recognition.[23,30,34] Today, many researchers have used this model by Morewedge and Kahneman to explore the effects of heuristics on judgment and decision-making processes related to the daily lives of individuals. Thus, confusion such as naming the heuristics that progress with similar cognitive processes with different names was prevented.[23,30]

Since the 2010s, science/chemistry educators have begun to explore in detail the roles of heuristics in students' reasoning processes related to chemistry subjects, and the working mechanisms of heuristics in the field of chemistry. The intuitive reasoning and heuristic uses of students in some chemistry subjects have been studied in detail in some research until today. Chemistry subjects explored in this context include chemical reactivity, bonding theories/molecular structures, addition reactions, IR and NMR spectra interpretation, chemical problem solving, elimination reactions, acidity/basicity strength of molecules, structure-property relations of molecules and classification of chemical substances.[2,11,23,26,29,35–37] The findings of these studies showed that due to the effects of intuitive judgments and heuristics, students generally answered the questions without using basic and significant chemistry knowledge. In addition to these studies mentioned above, in a theoretical study published in 2014, Talanquer explained ten heuristics that are likely to be used in chemistry subjects and the working mechanisms of these heuristics with examples specific to the field of chemistry.[10] The ten heuristics model of Talanquer has the quality to be used as a model in studies exploring the role of heuristics in the chemistry topics. For example, in three different studies recently conducted to examine the heuristic reasoning of students on "hydrogen bond" and "chemical structure – acidity/basicity relationship", the researchers carried out their research using the ten heuristic model.[38–40] Except for these three studies, there is no other study in the literature that explores the heuristics that are effective in chemistry topics based on the ten heuristic model proposed by Talanquer. These ten heuristics suggested by Talanquer are:[10]

Associative activation: Using mental structures present in memory to fill in the blanks.

Fluency: Using of easily accessible cues in the process of solving the problem.

Attribute substitution: evaluation of other easily accessible attributes instead of the target attribute / Substitution the original question with a simpler question.

One reason decision making: Simplifying reasoning by using a single clue or factor in the process of problem solving.

Surface similarity: The assumption that chemical compounds that are similar to each other in structural representation have similar properties and behavior.

Recognition: More value to recognized objects / less value to unrecognized.

Generalization: Generalization of learned models or rules

Rigidity: Reasoning in an inflexible or non-creative way.

Overconfidence: Exceeding true accuracy due to self-confidence in decision-making processes.

Affect: A positive or negative emotion towards an event, an object, or anything that affects learning.

The purpose of this study is to explore the effect of ten heuristics on the pre-service science teachers' reasoning processes about melting and boiling points. Therefore, the research problem of this study can be expressed as follows: What is the role of the ten heuristics in the reasoning processes of the pre-service science teachers on the melting and boiling points? The research questions of this study are as follows:

- Which heuristics affect the reasoning of the students in the process of performing a task in which the compounds are ranked according to their melting and boiling points?
- How to explain the working mechanisms of these heuristics in a way specific to the field of chemistry?

2. Method

2. 1. Participants

This research was conducted at Firat University in the spring semester of the 2018–2019 academic year. The participants of the study were selected on a voluntary basis, considering their successes in General Chemistry I and General Chemistry II courses from the students enrolled in the Science Education Program. Of the 30 teacher candidates who voluntarily participated in the research, 16 were male and 14 were female. 1/3 of the participants were students who failed in the General Chemistry I and General Chemistry II courses, 1/3 of them were moderately successful and 1/3 of them are highly successful. Participants were students enrolled in the 2nd, 3rd and 4th grades. In the study, the real names of the participants were not used, instead the participants were named with a coding S1, S2, S3, S4 … S30. The grouping of the participants according to their success in General chemistry I/II courses is as follows: Failed students; S1, S5, S7, S13, S14, S16, S18, S20, S23, S24; Moderately successful students; S2, S3, S4, S8, S10, S17, S21, S25, S26, S30; Highly successful students; S6, S9, S11, S12, S15, S19, S22, S27, S28, S29.

2. 2. Data Collection and the Interview Protocol

In this qualitative study, the phenomenological research method was used. The interviews were conducted with the participants in order to properly examine the heuristic reasoning of the participants regarding "ranking chemical compounds according to their increasing melting/boiling points". The interviews were conducted according to the following eight-step interview protocol:

I. How do you feel when talking about the ranking of compounds according to their increasing melting/boiling points? Have you ever experienced any positive or negative effects on this chemistry topic during your education? If so, does it still have any effect on you?

II. If you are faced with questions about ranking compounds according to their increasing melting/boiling points, what level of confidence do you have that you can answer the questions correctly? How would you score your confidence level between 1 and 10 points (1 is the lowest, 10 is the highest)?

III. Do you have a constant judgment/bias about the ranking of compounds according to their increasing melting/boiling points? For example, do you have any approaches such as "I have judgments/reasoning regarding the order of compounds according to their increasing melting/boiling points, which I will not change regardless of the question, I always solve problems regarding the order of compounds according to their increasing melting/boiling points using my current judgments/reasoning"?

IV. During the interviews, the following three questions about melting/boiling points were asked/showed to the participants:

1) Rank the HI, HCl, NaI, NaCl compounds according to their increasing boiling points.
2) Rank the HCl, HBr, NaI, NaBr compounds according to increasing melting points.
3) Rank the H_2Se, H_2S, PH_3 compounds according to their increasing boiling points.

Note: At this stage, the participants were given 2 minutes to answer each question. These chemistry questions were taken from a different study previously done by Maeyer and Talanquer.[6]

V. You saw the questions, what do you feel? (This question was asked just before students started answering relevant chemistry questions)

VI. What level of confidence do you have that you can answer these questions correctly? (This question was asked just before students started answering relevant chemistry questions)

VII. What level of confidence do you have in yourself that you answered these questions correctly? (This question was asked after students answered relevant chemistry questions)

VIII. Explain in detail the reasons for your answers to each chemistry question. (There was no time limitation at this stage.)

Note: During the interviews, some additional questions were asked in order to obtain more explanatory in-depth information.

The third question in the interview protocol was prepared to explore the effects of rigidity heuristic. Participants' answers to this question were carefully examined. In addition, during the interviews, special attention was paid to whether the participants actually solved the questions using the strategies they were used to before, and whether they were flexible in solving the questions. The rigidity heuristic was coded when it was determined that the participants were not flexible. The second, sixth and seventh questions in the interview protocol were prepared to explore the effects of overconfidence heuristic. In cases where 8, 9 or 10 points were given as an answer to the second, sixth and seventh questions, the overconfidence heuristic was coded. Students who gave such answers generally made the following statements: "I am confident; I definitely solved /will solve the questions correctly". The first and fifth questions in the interview protocol were prepared to explore the effects of affect heuristic. The affect heuristic was coded in cases where it was determined that the participant had negative or positive emotions due to experiences.

2. 3. Data Analysis

The interviews that were recorded with audio and visuals later were turned into written documents. Thus, interview transcripts were created for each student. With the analysis of the data obtained from the interview transcripts, heuristic reasoning was detected and coded. While coding, other similar studies on students' heuristic reasoning in chemistry were also used.[2,10,23,30,38] In order to ensure the inter-rater reliability, eight interview transcripts related to acidity strength and eight interview transcripts related to basicity strength (approximately 25% of total interview transcripts) were selected and the selected interviews were first evaluated and encoded separately by both the researcher and the consultant. The results of both evaluators were compared with each other. The encodings were revised so that there was over 90% agreement between the evaluators. After this compliance was achieved, all remaining interview transcripts were evaluated and coded by the researcher. Ten heuristics proposed by Talanquer[10] were used to create a coding scheme for heuristics. The heuristic encodings, except rigidity, overconfidence and affect, were carried out by associating the students' specific statements about the solution of the questions with heuristics. Specific student statements that are the basis of encodings were presented in the results and discussion section.

3. Results and Discussions

During the interviews, the following three questions about melting/boiling points were asked to the participants:

1. Rank the HI, HCl, NaI, NaCl compounds according to their increasing boiling points.
2. Rank the HCl, HBr, NaI, NaBr compounds according to increasing melting points.
3. Rank the H_2Se, H_2S, PH_3 compounds according to their increasing boiling points.

Table 1. Obtained Response Patterns

Response Pattern	Code name of students	n	%
	First question (Boiling point, HI, HCl, NaI and NaCl compounds)		
HI < HCl < NaI < NaCl	S1(F), S7(F), S11(HS), S21(MS), S23(F)	5	16.66
	HCl < HI < NaI < NaCl		
(Correct answer)	S9(HS), S12(HS), S20(F), S25(MS), S26(MS), S28(HS), S29(HS)	7	23.33
HCl < HI < NaCl < NaI	S2(MS), S17(MS), S19(HS)	3	10.00
NaCl < NaI < HCl < HI	S6(HS), S15(HS), S27(HS)	3	10.00
NaI < NaCl < HI < HCl	S4(MS), S14(F), S16(F)	3	10.00
HCl < NaCl < HI <NaI	S3(MS), S5(F), S8(MS), S10(MS), S13(F), S8(MS), S22(HS), S24(F), S30(MS)	9	30.00
	Second question (Melting Point, HCl, HBr, NaI and NaBr compounds)		
HCl < HBr < NaI < NaBr (Correct answer)	S6(HS), S9(HS), S12(HS), S20(F), S25(MS), S26(MS), S28(HS), S29(HS)	8	26.66
HCl < HBr < NaBr < NaI	S1(F), S2(MS), S3(MS), S5(F), S8(MS), S10(MS), S13(F), S17(MS), S18(F), S19(HS), S22(HS), S24(F)	12	40.00
NaBr < NaI < HCl < HBr	S15(HS), S27(HS)	2	6.66
HBr < HCl < NaI < NaBr	S7(F), S11(HS), S21(MS), S23(F), S30(MS)	5	16.66
NaBr < NaI < HBr < HCl	S14(F)	1	3.33
NaI < NaBr < HBr < HCl	S4(MS), S16(F)	2	6.66
	Third question (Boiling Point, H_2Se, H_2S and PH_3 compounds)		
$PH_3 < H_2S < H_2Se$ (Correct answer)	S1(F), S3(MS), S5(F), S6(HS), S8(MS), S9(HS), S10(MS), S12(HS), S13(F), S15(HS), S18(F), S19(HS), S22(HS), S24(F), S26(MS), S27(HS), S28(HS), S29(HS)	18	60.00
$H_2Se < PH_3 < H_2S$	S7(F)	1	3.33
$PH_3 < H_2Se < H_2S$	S4(MS), S16(F), S23(F)	3	10.00
$H_2S < H_2Se < PH_3$	S20(F), S21(MS), S30(MS)	3	10.00
$H_2S < PH_3 < H_2Se$	S2(MS), S17(MS), S25(MS)	3	10.00
$H_2Se < H_2S < PH_3$	S11(HS), S14(F)	2	6.66

Six different answer patterns were obtained for each question. Table 1 presents these different answer patterns, the code names of the students who gave these answers, the number and percentage of the students who gave these answers. The abbreviations in the form of F, MS and HS given in parentheses after the participant code names in Table 1 show the success of the mentioned student in General Chemistry I/II courses. F: Unsuccessful, MS: Intermediate successful, HS: High-level successful.

When the vapor pressure of a liquid is equal to the outside pressure (atmospheric pressure), evaporation begins to occur all over the liquid. This event is called boiling. The temperature at which the liquid begins to boil is called the boiling point. Boiling point is related to intermolecular forces. As inter-molecular forces grow, volatility and vapor pressure decrease. Therefore, boiling point increases. The interactions between particles in ionic bonded compounds are much greater than interactions in covalent bonded compounds. Therefore, the boiling points of ionic compounds are much higher than covalent bonded compounds. NaI and NaCl in the first question are ionic compounds. Their boiling points are much higher than those of covalent compounds HI and HCl. In order to compare the boiling points of ionic compounds among themselves, it is necessary to evaluate the charges and radii of the ions forming the compound. The greater the ion charge, the greater the interaction between the particles. The larger the ion radius, the weaker the interaction between the particles. On the differences between the relative values of physical properties, the effect of ion charge differences is more than the effect of ion radius differences. The charge values of the ions in both NaI and NaCl compounds are 1. The contribution of the charge values is the same. Therefore, radii are the factor enabling the comparison of inter-particle interactions for these two compounds. The cation part of these two compounds are the same. For this reason, the difference in the radii of the anion parts makes the interactions in NaI and NaCl compounds different. The radius of the iodine atom is greater than that of chlorine. Interactions in NaI compound containing iodine with greater radius will be less than interactions in NaCl compound. As a result, the boiling point of NaCl, which has a stronger interaction, is higher than NaI. Inter-particle interactions in covalent bonded compounds HI and HCl are dipole-dipole interactions and london forces (induced dipole-induced dipole interactions). The magnitude of the dipole – dipole interactions is related to the magnitude of the dipole moment values of the compounds. The dipole moment of a compound is related to the difference in electronegativity between atoms and the geometry of the compound. Dipole-dipole interactions of compounds with high dipole moment values are also higher. When considering for HI and HCl molecules with the same geometry; the electronegativity of the Cl atom is greater than the electronegativity of the I atom. Therefore, the electronegativity difference between hydrogen and chlorine atoms is greater than the electronegativity difference between hydrogen and iodine atoms. This ensures that the dipole moment of HCl is greater than the dipole moment of HI. Dipole-dipole interactions in HCl molecules with larger dipole moment are greater than dipole-dipole interactions in HI molecule. Another inter-particle interaction that is effective in HI and HCl compounds is london forces. London forces are related to the total number of electrons in the compound. The more electron-containing compounds, the greater the london forces. When considering for HI and HCl molecules; the london forces are higher in the HI molecule, whose total number of electrons is much more than HCl. When considering for these two compounds, the contribution of london forces to the interaction between particles is much greater than dipole-dipole interactions. In other words, the effect of london forces is more dominant in the comparison of the boiling points of these two molecules. As a result, the boiling point of HI, which has greater london forces, is higher than HCl. Because of all these explanations mentioned, the correct answer to the first question is $HCl < HI < NaI < NaCl$. Using the approaches explained in detail above, it will be seen that the correct answers for the second and third questions are $HCl < HBr < NaI < NaBr$ and $PH_3 < H_2S < H_2Se$, respectively.

Participants are expected to answer the questions with the reasoning explained in detail above. However, in this study, it was found that the rates of students who gave correct answers to the first, second and third questions were 23.33%, 26.66% and 60.00%, respectively. Because scientific reasoning requires a great deal of cognitive effort, the majority of students may have answered the questions by relying on heuristic strategies that require less cognitive effort. Since the aim of this study was to explore the heuristic usage of the students, students' answers have been analyzed in terms of heuristics used. Codes were made by associating the specific statements in the participants' responses with ten heuristics. Summaries of student statements that provide a basis to encodings about these ten heuristics were presented in Table 2. The periodic trends heuristic in Table 2 is not included in the ten heuristics proposed by Talanquer.[10] However, since it was found in this study that the participants also used this heuristic, this heuristic was also taken into consideration and added to the Table 2.

Table 3 presents the numbers and percentages of the participants who used the relevant heuristics at least once in the process of solving the questions, together with the code names of the participants who used these heuristics. The percentages given in Table 3 express the ratio of the number of participants who have used the relevant heuristics at least once to the total number of participants (N = 30, total number of participants). Question 1, question 2 and question 3 were abbreviated as Q1, Q2, and Q3, respectively.

Table 2. Heuristic codes and summaries of student statements (for three questions)

Heuristic code	Summary of student statements
Associative activation	The higher the molecular weight of the compound, the higher its melting / boiling point. The melting / boiling point changes from left to right and from top to bottom on the periodic table. The higher the acidity strength, the higher the boiling point. The higher the total number of atoms in the molecule, the higher the boiling point. Metal-containing compounds have high melting / boiling points. Strong acids have higher melting / boiling points than salts. The more electronegative, the higher the melting / boiling point.
Fluency	Using the numbers in the formulas of the compounds as an easily obtainable clue.
Attribute Substitution	Replacing the original question with questions: How are the compounds sorted according to their molecular weight? What are the positions of Na, Cl, H, and I atoms relative to each other in the periodic table? How are the positions of S, Se and P atoms relative to each other on the periodic table? What are the positions of Na, Cl, H, Br and I atoms relative to each other in the periodic table? Which compounds are acids and which are salts? Which atoms are more electronegative? Which compound is more acidic? Which compound has more total atoms?
One-Reason Decision Making	Decision making by only evaluating the molecular weights of compounds. Decision making by only evaluating the electronegativities of atoms. Decision making by only evaluating the acidity of the compounds.
Surface similarity	NaI is like NaCl / NaI is like HI / H_2S is like H_2Se / NaI and NaBr are like NaCl / HBr is like NaBr.
Recognition	I know/recognize NaCl or I know/recognize HCl.
Generalization	Generally, all properties increase/decrease from top to bottom in the periodic table, so the melting/ boiling point also increases/decreases from top to bottom. Generally, all properties increase/decrease in the periodic table from left to right, so the melting/ boiling point also increases/decreases from left to right. Atoms with high electronegativity generally have high all other properties. Strong acids generally have high all other properties.
Rigidity	I will decide with the principle of "the greater the molecular weight of the compound, the higher its melting/boiling point".
Overconfidence	I solved / will solve the problem absolutely correctly My confidence level is 8–10.
Affect	I like / dislike the melting / boiling point subject, positive / negative emotion
Periodic Trends *	The melting/boiling point increases/decreases from left to right on the periodic table. The melting/boiling point increases/decreases from top to bottom on the periodic table.

*Periodic Trends heuristic is not included in the ten heuristics proposed by Talanquer. However, this heuristic was added to the list since it was determined that the participants in this study also used this heuristic.

Individuals' unconscious replacing the question asked to them by another simple question and focusing on this different simple question is a result of the effect of attribute substitution heuristic.[30] In this study, it was revealed that heuristics affect the interpretation of the students about the questions, and thus there are differences between the target attribute and the comments expressed by the students. In the process of solving the first, second and third questions, it was found that 27 (90.00%) of the participants evaluated other attributes instead of the intended target attribute or unconsciously evaluated the intended target attribute due to the effect of attribute substitution heuristic. Thus, these students replaced the original questions with other simple questions after reading the questions. The mentioned students focused on the answers to other simple questions. These different questions were provided in Table 2 collectively.

It is reported in the literature that more than one heuristics are effective in decision-making processes of individuals and that these heuristics support and trigger each other.[10] Similar to this situation stated in the literature, in this study, it was concluded that more than one

Table 3. The number and percentages of participants who have used relevant heuristics at least once

Heuristics	n			% (N=30)			Students
	Q1	Q2	Q3	Q1	Q2	Q3	
Associative activation	27	27	27	90.00	90.00	90.00	S1, S2, S3, S4, S5, S6, S7, S8, S10, S11, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S24, S25, S26, S27, S29, S30 (for questions 1,2 and 3)
Fluency	–	–	7	–	–	23.33	S2, S11, S14, S17, S21, S25, S30 (for question 3)
Attribute substitution	27	27	27	90.00	90.00	90.00	S1, S2, S3, S4, S5, S6, S7, S8, S10, S11, S13, S14, S15, S16, S17, S18, S19, S20, S21, S22, S23, S24, S25, S26, S27, S29, S30 (for questions 1,2 and 3)
One reason decision making	9	9	13	30.00	30.00	43.33	S1, S3, S5, S8, S10, S13, S18, S22, S24 (for questions 1 and 2); S3, S4, S5, S6, S7, S13, S16, S18, S20, S22, S23, S27, S29 (for question 3)
Surface similarity	4	9	7	13.33	30.00	23.33	S6, S11, S21, S30 (for question 1); S6, S11, S14, S20, S21, S25, S26, S29, S30 (for question 2); S1, S8, S10, S15, S19, S24, S26(for question 3)
Recognition	8	8	–	26.66	26.66	–	S11, S14, S20, S21, S25, S26, S29, S30 (for questions 1 and 2)
Generalization	9	13	11	30.00	43.33	36.66	S2, S4, S7, S11, S16, S17, S21, S23, S30 (for question 1); S2, S4, S7, S11, S16, S17, S20, S21, S23, S25, S26, S29, S30 (for question 2); S2, S4, S7, S11, S14, S16, S17, S21, S23, S25, S30 (for question 3)
Rigidity	3	3	3	10.00	10.00	10.00	S15, S19, S22 (for questions 1,2 and 3)
Overconfidence	4	4	4	13.33	13.33	13.33	S9, S19, S27, S29 (for questions 1,2 and 3)
Affect	4	4	4	13.33	13.33	13.33	S1, S8, S9, S23 S29 (for questions 1, 2 and 3)
Periodic trends	4	4	4	13.33	13.33	13.33	S2, S7, S17, S25 (for questions 1,2 and 3)

heuristics were effective at the same time. The reasoning of one of the students (S10) for the first question can be given as an exemplary.

Q10: *For me, the correct order is as follows: HCl <NaCl <HI <NaI*

Interviewer: *Could you explain the strategy you used to answer the question?*

S10: *Boiling points are related to the molecular weight of the compounds. Compounds with large molecular weights have high boiling points. Therefore, the ranking I made according to increasing molecular weights is also valid for boiling points.*

It is reported in the literature that individuals frequently use one of the flat or inverse proportion approaches that can be summarized as "the more A – the more B" or "the more A – the less B" in cases where associative activation heuristic is effective.[10] From the statements of the S10 coded student, it is understood that the heuristics of associative activation and attribute substitution triggered and support each other in the process of problem solving. S10 coded student used the straight-proportion approach in the form of "the greater the molecular weight, the higher the boiling point" to solve the problem. This approach, which can be summarized as "the more A – the more B", is the result of the influence of the associative activation heuristic. This student evaluated another attribute (molecular weights of compounds) instead of the target attribute. This student unconsciously replaced the original question with another, simpler question (which compound is heavier?). This situation is a result of the effect of attribute substitution heuristic. Table 2 collectively presents the mental structures used by the participants to solve the questions.

Individuals generally facilitate reasoning by using a single clue or factor to give a logical answer. In doing so, they use the first feature that comes to mind. Individuals' making decisions in this way is a consequence of the effect of one-reason decision-making heuristic.[10] The S10 coded student made a decision based on only one reason. S10 coded student only evaluated the molecular weight of the compounds in the decision-making process regarding the question. For this reason, the one-reason decision making heuristic was also effective in the decision-making process of the S10 coded student.

For a person who is new to any field, it is easier to examine obviously given properties than implicitly given properties. People tend to use easily accessible information when making judgments and decisions. The use of easily accessible cues by individuals to solve the problem is associated with fluency heuristic.[10] The fluency heuristic is very often effective when there are explicit clues in the formulas or representations of molecules.[10] There are no parts in the compounds of HI, HCl, NaI, and NaCl that can be used by students as an easily accessible cue. For this reason, the heuristic of fluency did not affect the reasoning of the participants about this question. In the process of solving the second problem, no effect of fluency heuristic was found for the same reason. However, in the process of solving the third question (H_2Se, H_2S and PH_3 compounds), the effect of fluency heuristic was determined in the reasoning process of 7 (23.33%) of the participants. There are some parts in H_2Se, H_2S, and PH_3 compounds that can be used as easily accessible cues by students; while the number at the bottom of the hydrogen atom in the PH_3 molecule is 3, it is 2 in H_2Se and H_2S compounds. With the effect of fluency heuristic, some participants used this difference in numbers as a clue. The approaches of these participants were as follows: 1) "There are 3 hydrogens in the PH_3 molecule. The higher the hydrogen number in a molecule, the higher the acidity. Therefore, PH_3 is the strongest acid of these three compounds. The higher the acidity strength, the higher the boiling point. Therefore, PH_3 has the highest boiling point". 2) "PH_3 has 3 hydrogen atoms. The others are 2. The total number of atoms is higher in PH_3. Compounds with more total atoms have higher boiling points. Therefore, PH_3 has the highest boiling point. The reasoning of the S11 coded student in the process of solving the third question can be given as an exemplary reasoning process in which associative activation, attribute substitution and fluency heuristics are simultaneously effective;

> Q11: *For me the correct order is: $H_2Se < H_2S < PH_3$*
> *Interviewer: Could you explain the strategy you used to answer the question?*
> S11: *As the acidity of a molecule increase, its boiling point also increases. Each of the H_2Se and H_2S molecules have two hydrogens, while the PH_3 molecule has three hydrogens. Because it has more hydrogen, PH_3 has more acidity than others. Therefore, PH_3 has the highest boiling point. Since the hydrogen numbers of H_2Se and H_2S are the same, the acidities of these two compounds are close to each other. That's why I thought I should evaluate another parameter. I evaluated the electronegativities of the S and Se atoms in the compounds to determine the boiling points of these two compounds. Generally, all properties of atoms with high electronegativity are also high. S atom is more electronegative than Se atom. Therefore, the boiling point of H_2S containing the S atom is higher than the boiling point of H_2Se containing the Se atom.*

From the statements of the S11 coded student, it is understood that the heuristics of associative activation, attribute substitution and fluency triggered and supported each other in the process of solving the question. S11 coded student used the straight-proportion approach, "The more acidity of the molecule, the higher its boiling point" to solve the problem. This approach, which can be summarized as "the more A – the more B", is the result of the influence of the associative activation heuristic. Similarly, the approach "The more electronegative the atom in the molecule and bound to hydrogen is, the higher its boiling point" is also related to the associative activation heuristic. Solving the question with this kind of reasoning, the student evaluated other attributes (the acidity of compounds and electronegativities of atoms) instead of the target attribute. This student also unconsciously replaced the original question with another, simpler questions such as "which compound is the more acidic?" and "which atom is more electronegative". This situation is a result of the effect of attribute substitution heuristic. The student coded S11 used the numbers at the bottom of the formulas of molecules as an easily accessible clue. Therefore, the fluency heuristic was also effective in the reasoning process of the S11 coded student.

The extra generalization of the patterns or rules that individuals have learned using the knowledge they have gained from a few events that they have previously experienced, without considering all the variables, is considered as an effect of the generalization heuristic.[10] S11 coded students' approaches such as "*Strong acids generally have high all other properties*" and " *Atoms with high electronegativity generally have high all other properties*" show that the generalization heuristic is also effective in the reasoning process of the student. Student expressions showing that generalization heuristic is effective are given in Table 2 collectively.

Recognized objects or events have a strong influence on the decisions people make. If one of more than one object is recognized and the others are not, the recognized object is given a higher value. The fact that individuals give more values to recognized objects or give less value to unrecognized objects is considered the effect of recognition heuristic.[10] NaCl and HCl compounds are compounds that students often hear and recognize know from lectures, from the laboratory or from daily life. In the process of solving the first and second questions involving these compounds, it was determined that some of the students (26.26%) valued NaCl or HCl more due to the effect of recognition heuristic. For example, this kind of effect of the recognition heuristic was observed on the reasoning of the participant with code S30 in the process of solving the first question.

> Q30: *For me, the correct order is as follows: HI <HCl <NaI <NaCl*
> Interviewer: *Could you explain the strategy you used to answer the question?*
> Q30: *I know NaCl. It is table salt. I know it's solid. That's why I chose it as the one with the highest boiling point. NaI looks like NaCl. That's why NaI is probably also solid. I also know about HCl. The HCl is frequently mentioned in the lessons. It is also frequently used in chemistry laboratories. I know it is a liquid and a*

strong acid, as we use it many times in the lab. Strong acids generally have high all other properties. Therefore, its boiling point is also high. I have no information about HI. If it were strong acid, I would hear its name. It is probably a weaker acid than HCl. Therefore, its boiling point is lower than HCl.

The S30 student's statement that the NaCl compound, which s/he had previously known, is the compound with the highest boiling point among the compounds in the question is a result of the effect of recognition heuristic. The fact that S30 coded student gives less value to HI, which s/he did not know before, also shows that recognition heuristic is effective. The surface similarity heuristic was also effective in the reasoning process of the S30 student. The assumption that chemical compounds resembling each other in the structural representation are members of the same category and that such compounds have similar properties and behavior is a consequence of the effect of the surface similarity heuristic.[10] The student coded S30 thinks that the boiling point of the NaI compound is high because it resembles the NaCl compound. This situation is a result of the effect of surface similarity heuristic.

The reasoning of the S21 coded student in the process of solving the second problem can be given as another example in which the recognition and surface similarity heuristics are effective.

Q21: *For me, the correct order is: HBr <HCl <NaI <NaBr*

Interviewer: Could you explain the strategy you used to answer the question?

S21: *NaI and NaBr are ionic compounds. Their melting points are higher than others are. NaI and NaBr are similar to NaCl. I know NaCl. It is table salt and it is in solid form. It has a high melting point. Since they resemble NaCl, the melting points of NaI and NaBr compounds are also high. One of these two compounds has iodine and the other has bromine. In the periodic table, bromine is closer to chlorine. Therefore, when these two compounds are compared, the similarity of NaBr to NaCl is more. Since it is more similar to NaCl, the melting point of the NaBr is higher than that of NaI.*

Interviewer: *You said "the melting point of HCl is higher than HBr." Why is that?*

Q21: *I know HCl is a strong acid. I heard his name often in lectures. Strong acids generally have high all other properties. Therefore, the melting point of HCl is higher than the melting point of HBr.*

In this question about the melting point, the NaCl compound is not included. However, upon seeing the NaBr and NaI compounds in the question, the participant S21 came to mind the NaCl compound. This participant stated that he knew NaCl before and that its melting point is high. The participant mentioned also stated that NaBr and NaI compounds have high melting points due to their resemblance to NaCl. Participant with the code of S21 highly valued NaBr and NaI compounds because of the NaCl compound he knew before. Therefore, it can be said that recognition heuristic is effective in the reasoning process of the participant. In the reasoning process of the participant with the code of S21, the recognition heuristic and the surface similarity heuristic were dominantly effective. The student coded S21 thinks that NaBr and NaI compounds also have high melting points because they resemble NaCl. This situation is a result of the effect of surface similarity heuristic. H_2Se, H_2S and PH_3 in the third question are compounds that students do not know much. Therefore, the effect of recognition heuristic was not encountered in the process of solving the third question.

The affect heuristic was coded based on some important statements of the students with codes S1, S8 and S23. For S1, S8 and S23 coded students, the following are the expressions that form the basis for coding affect heuristic: "I hate verbal chemistry subjects", "I see myself closer to numerical logic", "I don't like dealing with abstract concepts and the relationships between them in chemistry lessons", "The issue of the relative ordering of compounds according to their melting/boiling points is the subject of verbal chemistry. Therefore, I do not like and are not interested in this topic". One of the participants (S9) stated that he liked the melting/boiling point topic and had a special interest in this subject. Based on this statement of the S9 coded student, the affect heuristic was coded for this student.

In this study, the procedure specified in the method section was followed to investigate the effects of rigidity heuristic. As a result of the operations performed according to the aforementioned procedure, it was concluded that the rigidity heuristic had an effect on the problem solving process of the students with codes S15, S19, and S22. The aforementioned students stated that no matter what the question was, they believed and trusted an approach to solving the question and that they would solve the question using this approach. The reasoning of the students in the process of solving the questions was examined carefully and it was determined that these students were not flexible in the process of solving the questions. The approaches that students have trusted are collectively given in Table 2.

In this study, the procedure described in the method section was followed to investigate the effects of overconfidence heuristic. As a result of the operations performed by following the mentioned procedure, it was concluded that the overconfidence heuristic was effective in solving the questions of the participants coded S9, S19, S27 and S29.

The heuristic of the periodic trends is not included in the ten heuristics proposed by Talanquer.[10] However, since it was determined in the study that the participants also used this heuristic, this heuristic was also taken into consideration. The heuristic of the periodic trends is also called arbitrary heuristic by some researchers. It is a result of the effect of periodic trends heuristic to make evaluations such as only the feature increases or the feature decreases without knowing why the features change from left to right and from top to bottom in the periodic table. It has been determined that this heuristic is effective in the reasoning processes of all three problems of the students coded S2, S7, S17 and S25. The associative activation, generalization, and attribute substitution heuristics also played an active role in many of the reasoning in which periodic trends heuristic exhibited. These heuristics have triggered and supported each other.

Studies in the literature on melting and boiling points report that students have difficulties in explaining the factors affecting melting and boiling events, and students have various misconceptions about melting and boiling phenomena.[1–6] The misconceptions frequently identified in studies in the literature regarding melting and boiling points are as follows: "As the molecular weight of the compounds increases, their melting and boiling points increase", "As the branching of the molecule increases, the melting and boiling points increase", "The higher the number of bonds in the molecule, the higher the melting and boiling points", "The higher the melting and boiling points of the oxygen-containing molecules." [2,5] Similar to what is stated in the literature, in the present study, it was found that students often had difficulties in understanding structure-property relationships, could not make accurate predictions or rankings about the melting and boiling points of compounds due to these difficulties, and they generally rely on short-cut strategies instead of scientific reasoning. The fact that in-depth interviews were made with the participants in this study, whose main purpose was to examine the heuristic reasoning of the students, also enabled the detection of some misconceptions in the students. The misconception that "melting and boiling points increase as the molecular weight of the compounds increases" reported in the literature was also detected in this present study. In the present study, the following two misconceptions were also detected; "Compounds with high electronegativity have higher melting and boiling points", "Strong acids have higher melting and boiling points".

The fact that the participants used heuristics frequently caused the rate of students who gave correct answers to the questions to be low. Similar to the results of the present study, in many studies on students' reasoning in chemistry subjects, it was found that the accuracy rates of participant responses were generally low. For example, in two different studies on students' understanding of hydrogen bonding, the accuracy rates of participants' answers were found to be 27% and 16.66%. [38,39] The accuracy rate of the participants' answers was found to be 36% in a study on "chemical bond theories and molecular structures", and 31% in a study on addiction reactions topic. [23,35]

There is only one study in the literature investigating the effects of heuristics on the process of ranking compounds according to their melting and boiling points. [6] The questions asked to the participants in the study conducted by Maeyer and Talanquer [6] and the questions asked to the participants in the current study are the same. In the study conducted by Maeyer and Talanquer[6], it was determined that the heuristics of "recognition", "one-reason decision making", "periodic trends" and "representativeness" were effective in the reasoning processes of the participants. In the mentioned study, explanations and comments were made based on these four heuristics. In the present study, the reasoning of the participants was examined on the basis

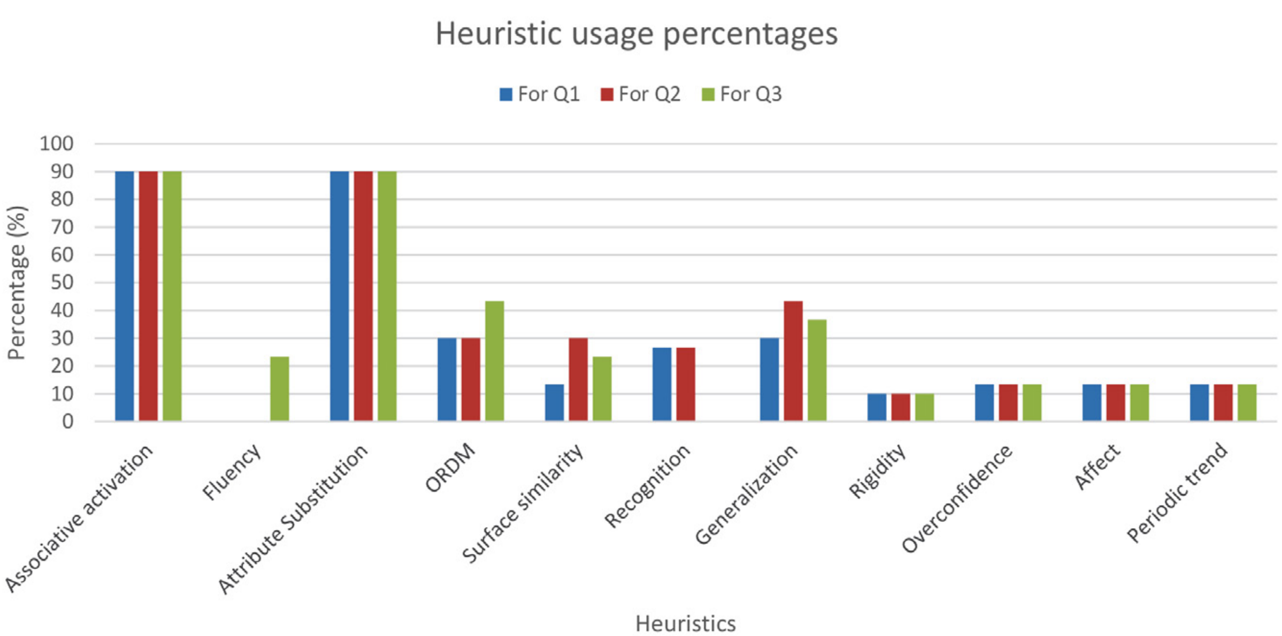

Figure 1. Graphical presentation of heuristic usage percentages.

of 10 heuristics. In order to present the results of the current research visually, the percentage of usage of the participants' heuristics is given as a graphical representation in Figure 1. Question 1, Question 2 and Question 3 are abbreviated as Q1, Q2 and Q3, respectively in Figure 1.

In the study conducted by Maeyer and Talanquer,[6] it was reported that the accuracy rates of student answers for the first, second and third questions were 5.90%, 8.80% and 20.60%, respectively. In this current study, in which students were asked to solve the same questions, the accuracy rates of student answers for the first, second and third questions were determined as 23.30%, 26.66% and 60.00%, respectively. Although the accuracy rates of student answers determined by the present study and the rates determined in the study conducted by Maeyer and Talanquer[6] were generally different, the accuracy rates of student answers were generally low in both studies. Only in the present study, the accuracy rate for the third question is partially high. However, the vast majority of students who answered the third question correctly in the present study answered the third question with an approach described as "the higher the molecular weight the higher the boiling point" rather than analytical reasoning. In the study conducted by Maeyer and Talanquer,[6] it was found that the percentages of participants who used one-reason decision-making, recognition and periodic trends heuristics in the process of solving the first problem were 70.60%, 52.90% and 14.70%, respectively. It was stated that these percentages were 82.40%, 26.50% and 11.80% respectively in the process of solving the second problem, and 73.50%, 14.70% and 44.10%, respectively, in the process of solving the third problem. In the present study, the percentages of participants using one-reason decision-making, recognition and periodic trends heuristics in the process of solving the first problem are 30.00%, 30.00% and 43.33%, respectively. During the solution of the second problem, these percentages were 26.66%, 26.66% and 0%, respectively, and in the process of solving the third problem, these percentages were determined to be 13.33%, 13.33% and 13.33%, respectively. The usage percentages of one-reason decision making, recognition and periodic trends heuristics determined in the study conducted by Maeyer and Talanquer[6] and the usage percentages determined in this present study are generally different. However, the explanations and determinations made in the present study regarding the action mechanisms of these three heuristics and the explanations and determinations made by Maeyer and Talanquer[6] are similar or the same.

This study revealed that pre-service science teachers rely on intuitive reasoning rather than analytical thinking when faced with questions about ranking compounds according to their melting and boiling points, and students frequently used heuristics. These heuristics reduced the cognitive effort in students and caused students to produce incorrect answers generally. Except for three studies on students' understanding of "hydrogen bonding" and "chemical structure – acidity/basicity relationship", the ten heuristic models proposed by Talanquer were not used in all other studies examining the effects of heuristics on chemistry subjects. With the current research carried out to fill this gap in the literature, the effects of all 10 heuristics proposed and defined by Talanquer on students' reasoning processes on the "melting and boiling points" were examined in detail.

4. Conclusions

The roles of all ten heuristics proposed by Talanquer in the process of ranking compounds according to their increasing melting and boiling points have been explored for the first time in this study. In this research, the melting and boiling point subject, which is a chemistry subject, has been evaluated and studied within the framework of a cognitive psychology theory. This study will make a significant contribution to the literature as it brings together different disciplines such as chemistry and cognitive psychology. The fact that heuristics have important roles in students' reasoning processes indicates that most students rely more on shortcut strategies rather than analytical reasoning. It is a known fact that cognitive constraints prevent scientific reasoning of individuals. The heuristics, whose working mechanisms are explained by this research, are typical examples of cognitive constraints that constrain students' scientific reasoning. The heuristics that the students had trusted, allowed them to make decisions without cognitive effort. However, due to these cognitive constraints, students' reasoning was often erroneous and students often gave incorrect answers. Knowing the students' thoughts and reasoning about melting and boiling points, as well as the role of heuristics in these processes, can help develop strategies that encourage meaningful learning about melting and boiling points. In order to develop measurement tools that will evaluate students' learning levels in chemistry subjects in a valid and reliable way, it is useful to examine students' reasoning strategies in detail. Therefore, this study may contribute to the development of measurement tools specific to the field of chemistry. For example, this study revealed that particular attention should be paid to the molecules or compounds involved in chemistry questions to be asked to students. In the first and second questions in this study, no effect of fluency heuristic was found, since there were no any explicit clue that the participants could easily obtain. However, an important effect of fluency heuristic was observed in the third question, as there was an explicit clue that the participants could easily obtain. In addition, the fact that the first and second questions included compounds such as NaCl or HCl that the students were recognized before caused the recognition heuristics to be used by some of the participants. Knowing these and similar situations and results will be useful for instructors who will prepare questions to evaluate students.

Forty percent of the students who had a high level of success in General Chemistry I/II courses answered the first question asked to them correctly in this study. For the second and third questions, these rates are 50% and 90%, respectively. 20% of the students who were intermediate level successful in the General Chemistry I/II courses correctly answered the first and second questions asked in this study. For the third question, this rate is 40%. Ten percent of the students who failed the General Chemistry I/II courses correctly answered the first and second questions asked in this study. For the third question, this ratio is 50%. These data show that students who are highly successful in general chemistry I/II courses have a higher rate of answering questions about melting and boiling points correctly than other students (who are unsuccessful or intermediate successful in general chemistry I/II courses). The percentage of students who answered the third question correctly is higher than the percentage of students who answered the first and second questions correctly. However, from the interview data analyzed in detail, it was determined that the majority of the students who answered the third question correctly answered the question without using scientific reasoning. It was determined that these students answered the third question using the approach of "the higher the molecular weight of a compound, the higher the boiling point", with the effect of associative activation heuristics. Regardless of their academic success in general chemistry courses, it is understood from a careful examination of Table 2 that heuristics are effective in the reasoning processes of the majority of students who answered the questions correctly or incorrectly.

As heuristic reasoning does not require cognitive effort and is fast and automatic, students often use it unconsciously. Developing effective and analytical reasoning skills instead of heuristic reasoning is a very time consuming and difficult process. Educating students in judgment and decision-making strategies can help students think effectively and analytically. Shortcut problem-solving strategies taught to students throughout their education life may have reduced students' tendency to use scientific reasoning skills. Thus, students may have acquired the habit of solving problems using shortcut strategies. Intuitive reasoning is one of the most commonly used types of reasoning. Therefore, it is important to investigate how intuitive judgment affects students' understanding and interpretation of chemistry topics. The data obtained from such research will be useful in creating successful reasoning and thinking methods specific to the field of chemistry. While teaching a chemistry subject to students, it can be very useful to explain to students the heuristic reasoning and the mechanisms of such reasoning that can make students mistake about that topic. It may be helpful to ask students to solve different types of chemistry problems in order to give students the habit of effective analytical and scientific reasoning instead of heuristic reasoning.

In this study, data were collected from a limited number of students enrolled in the Science Teaching Program of Firat University. As a necessity of the interview method, the fact that a small number of participants were interviewed is a limitation of this study. For this reason, we recommend that similar studies be carried out in different institutions. The participants who were interviewed within the scope of this study were determined on a voluntary basis and no reward was given to these participants for their time and effort. Another limitation of this study is the possibility that this situation negatively affects the students' motivation to spend time and their cognitive efforts to answer the questions. More studies are also needed on how System 2 processes can be activated more to correct biases caused by System 1 processes in different chemistry issues. In addition, it is beneficial to investigate the effects of various teaching strategies that will be planned to eliminate the negative effects of heuristics that affect chemistry subjects.

Conflicts of Interest

There are no conflicts of interest to declare.

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Povzetek

Namen raziskave je bil proučiti učinke hevristike na procese sklepanja kandidatov za učitelje naravoslovja na temo tališča in vrelišča z uporabo desetih hevrističnih modelov, ki jih je predlagal Talanquer. V tej fenomenografski raziskavi, opravljeni v spomladanskem semestru študijskega leta 2018/19, so bili opravljeni razgovori s 30 bodočimi učitelji, ki so bili vpisani v program za izobraževanje na področju naravoslovja Fakultete za izobraževanje Univerze Firat. Udeleženci so morali med intervjuji odgovoriti na tri različna vprašanja. Vprašanja so se nanašala na razvrstitev nekaterih spojin glede na njihovo tališče ali vrelišče. Iz odgovorov smo dobili šest različnih vzorcev odgovorov za vsako vprašanje. Ugotovitve te študije so pokazale, da so študentje na splošno uporabljali strategije bližnjic namesto analitičnega/znanstvenega sklepanja, saj je vseh deset hevristik vplivalo na razmišljanje udeležencev. Ta študija je tudi pokazala, da čeprav hevristični periodični trendi niso vključeni v model, ki ga je predlagal Talanquer, so vplivali tudi na razmišljanje udeležencev o tališču in vrelišču.

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