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Intuitive Judgments Govern Students' Answering Patterns in Multiple-Choice Exercises in Organic Chemistry

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ABSTRACT: Research in chemistry education has revealed that students going through their undergraduate and graduate studies in organic chemistry have a fragmented conceptual knowledge of the subject. Rote memorization, rule-based reasoning, and heuristic strategies seem to strongly influence students' performances. There appears to be a gap between what we believe students understand in organic chemistry and what they actually learn. In this report, findings are presented on how intuitive judgment processes governed organic chemistry students' unsuccessful and successful answering patterns in a traditional set of multiple-choice items. Analyzing the participants' approaches through the lens of associative processes in intuitive judgments contributes to the ongoing discussion about appropriate assessment in organic chemistry and encourages the improvement of the traditional curriculum in the discipline.

KEYWORDS: *Second-Year Undergraduate, Organic Chemistry, Chemical Education Research, Testing/Assessment, Addition Reactions*

FEATURE: Chemical Education Research

In psychology, it has been thoroughly discussed that there are two different ways to cognitively process information, which govern significantly our decision-making.[1−4] The "dual-process" model of reasoning divides the human reasoning processes into type 1 processing, which is based on intuitive, automated, and less effortful reasoning, and type 2 processing, which involves elaborative, logical, and rather time-consuming reasoning strategies.[4] The human information processing system tends to use easy-to-access information to make fast, adequate, and sometimes imperfect decisions.[5,6] Those shortcut reasoning procedures are described in terms of heuristic strategies that allow "decision makers to process information in a less effortful manner than one would expect from an optimal decision rule."[6]

In the past several years, research efforts in chemistry education have recognized the diverse influences of intuitive thinking in students' learning and decision-making processes and have come to acknowledge the existence of students' use of heuristics[7,8] and the value of heuristic thinking in organic chemistry.[9,10] Some traditional guiding heuristic principles taught in the classroom can help to reduce the cognitive load on students, as they are easy to memorize; however, they can result in students adopting alternative and oversimplified conceptions. For example, students are taught to use "the octet rule" as a simple rule of thumb to estimate the stability of a compound; yet, it may distort their ability to grasp the underlying concept.[11] Numerous cognitive biases that have been observed in students' reasoning while ranking chemical substances,[12] making decisions about the acid strength of common organic molecules,[13] and estimating common structure−property relationships in organic[14] and general chemistry[15,16] have been shown to result from various heuristic strategies. These heuristics have allowed students to answer questions correctly without a substantial use of chemical knowledge. Students' reasoning has been shown to be prone to surface level features, such as the functionality of organic compounds,[17] and rarely goes beyond the external representation.[17,18] Comparable results have been documented in other studies that examined students' mechanistic problem-solving,[19] arguments about organic reactions,[20] and understanding of electron-pushing formalism in organic chemistry.[21−23]

The existing research results raise important questions about what governs students' learning and reasoning in organic chemistry and consequently what is actually measured in assessments. On the basis of an analysis of student answering patterns in science, Heckler concluded that, in the context of science, we still have the tendency to believe that correct answering patterns can often be explained by the application of correct concepts and incorrect answers are the result of misconceptions or incorrect concepts.[24] The ongoing research on students' reasoning in organic chemistry has allowed us to recognize that not only failure but also success in assessment can be strongly influenced by domain-general intuitive thinking and may not always be based on chemical understanding. This growing awareness that less effortful cognitive processing in our everyday decision-making also plays an important role in science teaching and learning is the initial step to appropriately teach and assess in chemistry.[9] During our ongoing work, which focuses on students' sense-making procedures in organic chemistry, we recurrently observed that students rely on type 1 processing. This gave rise to successful answering patterns, but also to major biases, such as assumptions that "syn-addition" and "concerted reaction" are alike.

Successful and unsuccessful answers may be based on similar shortcut strategies rather than on differences in students' chemical understanding. Upon the basis of this premise, this study was conducted to explore the influence of fundamental intuitive judgment processes on student answering patterns in a traditionally used exercise format.

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Table 1. Associative Memory Processes in Intuitive Judgments

Type 1 Associative Memory Processes[5]	Application as Decision-Making Strategy
Attribute Substitution	A rather complex judgment, such as a fairly inaccessible target attribute, is substituted with a simpler attribute that is related to the target but remains highly accessible through perception or priming.
Fluency Processing	People use easy-to-access information to make a decision. The unconscious selection of the used cues facilitates a fast search and decision-making.
Associative Coherence	People make decisions based on what they associate with a given context, text, or speech, although this association may not be explicitly mentioned. An association is generally triggered by certain cues.

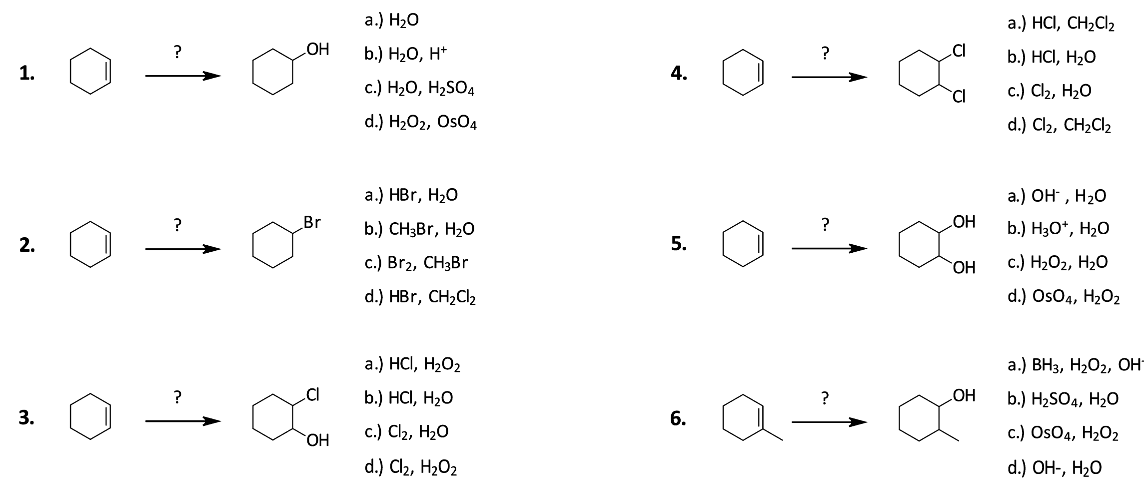

Figure 1. Multiple-choice instrument.

THEORETICAL FRAMEWORK

Various intuitive strategies have been identified and described in cognitive psychology research and have often been classified based on terms used in psychology, or the study context, such as the price heuristic[25] (which describes that people perceive expensive products to be of high quality). Over time, the variety of heuristic strategies has increased and the boundaries of each strategy have become vague. Many heuristics documented in the literature are domain-specific instantiations of domain-general principles, which are generally named by the corresponding context of the study, but which are often based on the same cognitive process.[6] Some research efforts have thus been made to categorize heuristic strategies based on the similarity of the underlying cognitive process. Morewedge and Kahneman[5] focused in their research on the nature of the readily available information activated from memory and used to make decisions and judgments. As such their model combines commonly cited heuristics, such as recognition,[26] availability, and representativeness.[27] They describe how type 1 processing operates with three different features of associative memory that influence and support the decision-making process: attribute substitution, fluency processing, and associative coherence (cf. Table 1). These associative processes help explain the source of judgment errors and successes made during a decision-making process.[5,28] The decision-making strategies work in conjunction with one another and reinforce themselves.

An example to illustrate these theoretical constructs in the context of chemistry is to look at reported reasoning behaviors of students while engaged in determining the acid strength of substances.[13] Students tend to answer questions comparing the acid strength of substances by determining the amount of hydrogens that they find in two different compounds (attribute substitution). The triggered association is "hydrogens are responsible for acidic solutions" (associative coherence), and determining the amount of hydrogen is easy-to-access information (fluency processing). While relying on these shortcut strategies, a diprotic acid, such as phosphoric acid, is perceived to be more acidic than a monoprotic acid. However, in the context of comparing sulfuric acid and hydrocyanic acid, only considering the amount of hydrogen possible provides the correct answer. These strategies reduce a multivariate decision-making process, such as considering bond strength, polarity or electronegativity to determine acid strength to a manageable set of easier questions that can govern the decision-making process. Depending on the exercise design, it can be very effective to get the correct answer. Thus, what may be considered as a correct or incorrect answer may result from a simplified shortcut-reasoning strategy and may neglect chemical content knowledge.

Morewedge and Kahneman's model presents the effects of associative memory and focuses on the types of associations activated during decision-making processes. Thus, this allows to describe students' sources of reasoning through the lens of their intuitive associations, instead of classifying them based on the catalogue of different heuristic strategies. This model allows description of the observable associations that an exercise initiates and does not require to differentiate between an availability heuristic and a representativeness heuristic.

This perspective is not only valuable from a cognitive psychology standpoint, as it sheds light on students' knowledge organization strategies, but also outlines the students' intuitive associations activated in a particular exercise context.

METHODOLOGY

The present study was conducted as part of a larger qualitative project on cognition in organic chemistry which is reported in detail elsewhere.[29] The main objective of the overall project was

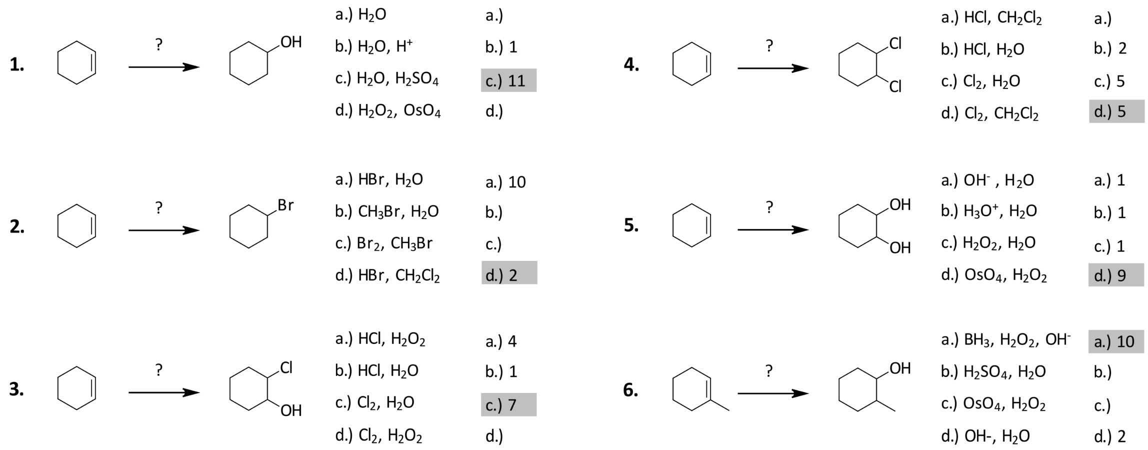

Figure 2. Multiple-choice items showing response distribution patterns. Correct answers are marked in gray; $N = 12$.

to analyze students' approaches while judging the similarity and difference of organic reactions.

The purpose of the investigation reported herein was to explore the effects of associative memory processes on students' decision-making processes while engaged in answering a common type of multiple-choice items on organic addition reactions. The chapter on addition reactions is one of the first topics that students learn in the organic chemistry classroom and can be considered exemplary on how students start to reason in organic chemistry. Furthermore, this topic is appropriate to investigate how students connect surface features with embedded chemical knowledge, as addition reactions appear to be highly similar, but proceed through different mechanistic processes.

The study was conducted in the department of chemistry at a large, research-oriented university in the southeastern United States during the fall 2013. Twelve undergraduate students, enrolled in an introductory organic chemistry class for nonmajors, were recruited on a voluntary basis. More than half of the volunteers, mostly chemistry majors and bioengineers in this study were at the mid-range performance of this large organic chemistry class and had passed the general chemistry classes. The typical exercise formats used in this organic chemistry class were a mixture of classical exercise formats and multiple-choice exercises. To protect their identity, pseudonyms have been assigned to each participant. For the purpose of this study, we used six different alkene addition reactions taken from the current lecture and designed six multiple-choice items (Figure 1) in the "supply reagent, given starting material(s) and product(s)" format. The selection of the addition reactions used for the items was made based on the reactions' occurrence in this traditionally taught lecture.

"Give the right reagent" formatted exercises have been chosen, as the design of "Give-the-product" multiple choice exercises in the case of addition reactions does not allow to generate comparable and plausible distractors. As students' reasoning is highly constrained to surface-features and relies on recognition,[12,13,15] we aimed at designing the options of the items with a high degree of surface distractors, as exemplified by the options given in the halohydrin formation in item 3 (Figure 1). The surface similarity of the options was meant to trigger possible associations that students might use to differentiate between the options' perceptible similarities, such as considering possible alternative mechanistic paths to exclude option a. HBr/H_2O in item 2 (Figure 1).

The data collection took place following the exam assessing addition reactions. During the approximately 45 min interviews, participants were asked to think out loud as they determined the appropriate reagents of the multiple-choice items and to elaborate on the reasons for their decision. To gather the students' responses and answers simultaneously, as well as to capture possible changes to their answers, the program ExpoBoard was used to audio- and videotape the interviews. After the data collection was completed, the interviews were transcribed verbatim.

The interview data was analyzed using an a priori coding scheme based on Morewedge and Kahneman's model, looking specifically at participants' quotes that accounted for (1) the participants' search strategy to choose an answer, (2) fluency effects, and (3) associations mentioned to differentiate between options. The used coding scheme was further informed through existing research on heuristic reasoning.[12,13]

■ RESULTS AND DISCUSSION

The multiple-choice items and corresponding answering patterns of the participants, represented by the corresponding numbers for each option, are shown in Figure 2. The numbers marked in gray refer to the number of students that selected the correct answer, resulting in a total correctness of 31%. This percentage only represents how often the participants picked the intended right answer and does not imply the correct use of chemical knowledge.

The analysis revealed that a significant proportion of the participants' decision-making processes (95% of all cases) strongly relied on one or more of the three associative memory processes to complete the multiple-choice items; this reliance resulted in successful as well as unsuccessful answering patterns. We organized the findings based on how the three intuitive effects—*attribute substitution*, *fluency*, and *associations*—influenced the participants' search strategies and answering patterns.

Attribute Substitution Effects in the Initial Decision Phase

In general, the initial step to approach a multiple-choice question is to determine what the task is asking for. This might seem trivial, but a closer look at the participants' approaches revealed that an attribute substitution effect shifted their interpretation of the given question. There is a difference between the intended *target attribute*, which was to evaluate the process that the reagents induced to lead to the product based on an evaluation of the chemical reaction process, and the actual interpretation expressed by the participants. All but one of the participants' initial approaches seemed to neglect the underlying, mechanistic information and did not consider the intended *target attribute*. The predominant attribute substitution effect shifted more than half of the participants' search toward recalling learned reagents for the displayed reactions and substituted the question: "What reagent is responsible for this reaction to occur?" with a simpler one: "Where do I see the reagent for this reaction that I learned in class?", as illustrated by Hanna's quote regarding item 1.

> Hanna: *I choose that one* (referring to c. (H_2SO_4/H_2O) in item 1, the hydration reaction). *I think just because I'm doing this in class right now. I know the addition of water. Sulfuric acid adds the OH and than the H. So, I don't know exactly why, I just remember it from doing in class.*
> Interviewer: *Can you explain what your strategy is to find the answer?*
> Hanna: *I just saw it in class and learned it. I guess that is what I do. I'm looking for what I know.*

A third of the participants approached the items with a slightly different question: "Where do I see the best fit between the composition of the reagent and the detected change going from reactant to product?" The original task was thus reduced to determining the occurred change from starting material to product by looking for the source of the substituents on the surface level. Those participants started the decision-making process by splitting reagents into their atoms and distributing them over the double bond. Molly's quote illustrates how that focus governed the search strategy for the halohydrin formation in item 3.

> Molly: *The third one* (referring to item 3, the halohydrin formation), *this one makes sense* (she chooses b. (HCl/H_2O)
> Interviewer: *What made you choose b. (HCl/H_2O)?*
> Molly: *It will give me a product with a chlorine, and the water gives me an OH to put on the product as well.*
> Interviewer: *So what is your strategy?*
> Molly: *I kind of try to find where to get the Cl and the OH from to make that product.*

This attribute substitution effect has been shown to normally occur without any awareness[28] and was reinforced in the case of this study by the fluency effect as the participants' focus shifted to surface cues (i.e., identifying the learned reagents or relating the change in functionality to the atomic composition of the reagents). Attribute substitution induced a reduction of complexity by an unconscious elimination of the amount of information necessary for a search. This allowed access to highly available information, by recognizing a hydroxyl group (−OH) in the product and relating it to H_2O as its source on the atomic level.

Although one might assume that multiple-choice items may have enhanced this attribute substitution effect, it is nevertheless important to be aware that "give-the-product" exercises may elicit the same effect and students' answering patterns may not be based on the intended thought process. The ease with which the students expressed the attribute substitution suggests that this strategy is commonly used and not only encouraged through multiple-choice exercises.

Fluency Effects

According to Shah and Oppenheimer "fluency is not itself used as a cue for judgment, but instead manipulates which strategies or cues are used to confront a task."[6] The fluency effect thus revealed to be the most predominant of the three associative processes in the participants' decision-making processes, reinforcing the attribute substitution effect and the recall of intuitive associations by reducing the focus of the search to easy-to-access surface features.

During the step of choosing an answer, the participants mainly used surface cues, either by recognizing from memory or by matching the particular atomic composition of a reagent to the product substituents. The total amount of decisions made by the participants has been categorized based on surface-matching procedures (33%), the recognition of a learned reaction (55%), process-related chemical knowledge (9%), and random choices (3%). Gabriel's thought process exemplifies the surface-matching strategy and illustrates how surface cues were used to search for a source of the substituents in item 4, the chlorination reaction.

> Gabriel: *So the next one* (referring to item 4, the chlorination), *it could not be b. (HCl/H_2O) because it has only one chlorine and a. (HCl/CH_2Cl_2) has a chlorine here (refers to the HCl) and here (refers to the dichloromethane). And c. (Cl_2/H_2O) and d. (Cl_2/CH_2Cl_2) have both two chlorines. I would say it is not d. (Cl_2/CH_2Cl_2). So I would choose between a. (HCl/CH_2Cl_2) and c. (Cl_2/H_2O). (pause) I want to go with c. (Cl_2/H_2O) that is the best choice I guess, because I'm not really sure with CH_2Cl_2. If the chlorine in a. (HCl/CH_2Cl_2) from CH_2Cl_2 goes on this carbon and the other chlorine from HCl goes on to the other carbon. Then the left over in the solution would be a CH_2Cl. I don't know if this okay or not. I'd rather go with c. (Cl_2/H_2O).*

This example shows how supplementary and unfamiliar cues, such as dichlormethane, can be a source for biases, as the surface-matching strategy depends on the set of reagents presented. This means that including solvents (e.g., in the chlorination reactions) distracted the participants. In the latter part of the quote, Gabriel's fluency with water instead of dichlormethane led her to decide to take Cl_2/H_2O instead of the correct answer Cl_2/CH_2Cl_2. Both choices seemed to fulfill the search strategy and the greater fluency with one of the solvents determined her final choice.

This may be explained by the fact that textbooks generally have the tendency to present the addition reactions with the only active reagent. Thus, several participants, who were not able to recognize directly the right combination of reagents, tend to "distribute atoms over the double bond" and considered additional solvents as possible active reagents. A simplified representation while learning an addition reaction may trigger a simplified surface memorization when students do not need to make a distinction between active reagents and solvent molecules. In a simple reaction with one reagent given (e.g., addition reaction with HBr or Cl_2), matching surface cues can be quite successful when no additional solvents are added.

The reliance on recognition represents a very promising strategy for the participants because recognizing a learned set of reagents for a reaction offered a high probability of success in the context of the multiple-choice items and may work successfully in "give-the-product" exercises as well. Particularly in items 1, 5, and 6, the recognition effect was prevalent and explicitly mentioned by the participants as the basis for 90% of the correct answers in these items. However, a substantial proportion of the participants in this sample were often not able to further explain the underlying chemical process, and the knowledge recalled remained fragmented, as shown in Hanna's quote

> Hanna: *In the next one, I know this. This one* (referring to item 5, the dihydroxylation with OsO_4) *for sure makes two alcohols. The last one* (referring to item 6, the hydroboration), *this is BH_3. This is anti-Markovnikov reaction and normally the OH should be on the most substituted carbon and its not. So, that for me eliminates the other choices.*
> Interviewer: *Can you explain how BH_3 reacts in this reaction?*
> Hanna: (pause) *I don't know really. At some point the OH should come in. I don't know, I just remembered it from class.*

Given the prospect of success while using recognition, it is not surprising that students overemphasized the memorization of reaction patterns, as a successful recognition can correct an initially unsuccessful matching approach. The recognition effect easily fails when reactions require a specific set of reagents. This became evident in item 5, the syn-dihydroxylation with OsO_4 and in item 6, the hydroboration reaction, where matching reagents and product substituents is not directly possible, as shown in James's quote.

> James: *The next one* (referring to the item 5, dihydroxylation with OsO_4), *the only one that makes sense to me is c. (H_2O_2/H_2O), because of two Hs and two Os and nothing else.* (pause) *The last one* (referring to item 6, the hydroboration) *I would go with d. (OH^-/H_2O), because there is just an OH that its been added. So that makes sense to take that.*

This case illustrates further why the participants generally have a high tendency to rely on memorization and recognition, as the matching procedure is not a good choice in these cases. The answering pattern for the hydrobromination reaction, item 2, serves as a good example of how an overreliance on fluency triggered option a. (HBr/H_2O) instead of d. (HBr/CH_2Cl_2). Seven out of the 10 participants who picked option a. (HBr/H_2O) went straight to this option. In the three remaining cases, the participants expressed their confusion because of the presence of water, as this would give water in their opinion. However, the recognition of the HBr seemed to overrule the associations that were activated through the presence of the water, namely "water makes alcohols" (3 participants).

> Interviewer: *What are you thinking?* (Eaden is looking at item 2, the hydrobromination)
> Eaden: *I am trying to find a Br and just an H, so the water confuses me. I feel like that would add an OH somewhere in there. I don't know.* (pause) *But I think I will go with that one (referring to a. (HBr/H_2O)), because I don't know. The rest of these, I took these out. I need an H and a Br. Usually I just used to see the HBr without the water, so I'm confused, but anyway I'll take that.*

If the water was missing in this item, the answer would be considered correct, even though the expressed reasoning behind cannot be considered chemically appropriate because it lacks mechanistic information or chemical reasoning. The main hindrance to successfully determine if the water might be involved in option a. HBr/H_2O is the missing reasoning about the mechanistic path, which might give a hint on competing nucleophiles.

Fluency was thus a strong source for both failure and success in this study context and depended highly on the surface cues.

Intuitive Associations

In the course of the decision-making process, the participants evaluated other options and explained their own choices by using various associations about the reagents. The aspect of fluency that governed their cue selection seemed to also have an effect on the nature of the associations and assumptions they used to decide between options. The commonly expressed associations were in most of the cases related to the product appearance and expressed in terms of associating function to a reagent, in the "x makes y" or "x does y" format (e.g., "Cl_2 makes two chlorines"). Some associations, such as "X_2 makes two halogens" and "HX makes one halogen" were used very consistently and mentioned by all participants in the sample for items 2−4.

The following quote from Nathan illustrates the observed trend that several participants showed while choosing option a. (HBr/H_2O) instead of d. (HBr/CH_2Cl_2) for the hydrobromination, item 2. Associating properties to the other available options helped to eliminate them and reinforce the decision.

> Interviewer: *So what made you choose that option a. (HBr/H_2O) instead of the others?*
> Nathan: *With the Br_2 reactions, this one* (referring to c. (Br_2/CH_3Br)) *would leave it with two Brs on the double bond. HBr gives one Br. And d. (HBr/CH_2Cl_2) the hydrobromination down here, it would have added that methyl group, instead of a hydrogen. I think there would be a methyl group. But I think it may take one chlorine with it.*

A very prominent association activated in this sample was the "water makes alcohol" and "water is the solvent" association. These two notions seem to be triggered dependently on the product's appearance rather than the underlying process of the reaction. Especially in items 2−4, the use of these associations for the decision-making process led to successful as well as unsuccessful answering patterns. The "water is the solvent" association was expressed more often when no hydroxyl group (−OH) was present in the product, as in item 2 and item 4. This leads to a wrong answering pattern in ten cases for item 2 and seven cases for item 4. The notion of "water makes alcohol" was mentioned when a hydroxyl group (−OH) was present in the product. The following quote from Hanna exemplifies how the use of these associations changed depending on the product appearance context, going from item 3, the halohydrin formation, to item 4, the chlorination.

> Hanna: *The next one* (referring to item 3, halohydrin formation) *is* (pause) *b, (HCl/H_2O). I picked that one, because there is just only one Cl and the H_2O adds the oxygen to the H. The next one* (referring to item 4, the chlorination) *I would say it is c. (Cl_2/H_2O), because Cl_2 would add two chlorines.*
> Interviewer: *In the last exercise you said the water adds the OH. What about in this reaction?*
> Hanna: *I don't know, I guess it is just the solvent. I just know when I have these two options, one with H_2O* (referring to c. (Cl_2/H_2O)) *and one with CH_2Cl_2* (referring to d. (Cl_2/CH_2Cl_2)), *I pick this one* (referring to c. (Cl_2/H_2O)), *because I feel like if this would be included* (referring to the CH_2Cl_2) *there might be more chlorines involved in the product.*

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This case illustrates how the fluency effect seems to direct which associations are activated in the participants' decision-making processes, resulting in a strong focus on surface features and neglecting the actual, underlying mechanism. This was a common pattern among the participants that resulted in successful answering patterns, as seen in five out of the 12 participants who successfully used "water makes alcohol" associations for item 4, the chlorination.

> Marc: *I definitely need two Cls* (referring to item 4, the chlorination reaction), *which I'm thinking Cl_2. But I don't want Cl_2/H_2O, cause this will give just a Cl and alcohol. I'm trying to decide between a. (HCl/CH_2Cl_2) and d. (Cl_2/CH_2Cl_2), because I don't want to have any H_2O in there. We don't normally have X2 and then something else. I'm trying to think if I* (pause) *would go with this one* (referring to the d. (Cl_2/CH_2Cl_2)) *and I would say that this* (referring to the CH_2Cl_2) *does not react.*

In this case, the "water makes alcohol" association served as a mean to eliminate the options with water as a reagent. Additionally the recall of "X2 makes two halogens" associations allowed participants to successfully exclude option a. (HCl/CH_2Cl_2).

These simplified associations between a reagent and its possible effect in a product facilitated the decision-making process as the participants could remain on the surface level and make fast decisions. These associations mirror the common focus on functional group change in an organic chemistry classroom. However, the major trend observed throughout the decision-making processes revealed that, after prompting, the participants were not able or struggled to verify the trustworthiness or validity of their associations by recalling the chemical mechanisms or other knowledge pieces to confirm their assumptions. Kahneman described this behavior as an "overconfidence in judgments," and a high confidence in associations depends on the coherence between "the evidences" and the "story" that is constructed.[5] Hence, mainly compatible associations are evoked for the options that supported and reinforced the decision-making process, as seen in Marc's quote above.

Relating the circumstances in which a particular association had been triggered to the particular item design was difficult. Future research needs to investigate the cue-association connection and the circumstances in which particular associations are more easily activated than others.

■ IMPLICATION FOR FUTURE RESEARCH AND INSTRUCTION

The participants' strategies described here bring into question what is actually assessed by using questions in which students have to supply a reagent given starting material(s) and product(s) or predict a product given starting material(s) and reagent(s). Even in the tasks used in this study, with a high degree of surface similarity between the different reagent choices in each question, the students were generally able to successfully solve the tasks by using their shortcut strategies. While it is tempting to conclude that the answering pattern provides evidence of students looking past surface-level strategies, the data herein indicate otherwise. According to the students' explanations, they considered each option for the briefest of times in their search for something familiar. As such, they were able to successfully solve many of these tasks by domain-general shortcut strategies, rather than applying chemical knowledge. However, given the exploratory nature of this study, we have to acknowledge that the data neither determines why students are not using chemical understanding nor if they opt not to use it. None of the participants intended voluntarily to use the mechanism to differentiate between options and prompting them to elaborate on their decision did not encourage them to recall mechanistic information.

The analysis indicates that the current practice in organic chemistry instruction seems to trigger the development of very effective strategies, which are not necessarily based on "chemical plausibility" and may strongly affect future content acquisition. This encourages a critical trend, however conscious or unconscious it may be. We value those students who make use of shortcut reasoning strategies that get them to the correct answers, and we may lose those students who seek a deeper understanding.

The study reported therein adds to the ongoing research on students' reasoning in chemistry and further supports the need to clarify the source of intuitive assumptions and possible ways for its regulation. Intuitive thinking is a very human behavior and we should not strive to eliminate this type of reasoning in the classroom. Our role as teachers and educators is to diagnose the effects of intuitive thinking on students' understanding and to find ways to build successful domain-specific thinking. It would be beneficial to determine to what extent shortcut reasoning strategies are emphasized in a general chemistry classes and how this affects the content acquisition in organic chemistry.

Additionally, we should explicitly focus future research efforts on developing exercises and learning scenarios that access students' reasoning behind an answer, such as two-tier multiple-choice exercises,[30,31] and encourage students to explain their choices and understanding.[32] Furthermore, this study suggests the importance of varying the exercises used to learn in organic chemistry to avoid a domain-specific test-wiseness effect.[33] Going beyond the traditional "Give-the-product" formats, which generally focus on recalling the product, and implementing a broader variety of exercise formats, such as compare-contrast exercises, may elicit students' reasoning and necessitate students' use of chemical knowledge. Mechanisms should be used as a tool to make predictions and to decide between two products or mechanistic steps, and rather as a filling between starting material and product. It would be valuable for future instruction to determine which type of exercises actually triggers students to apply chemical knowledge in their decision-making process.

Lastly, another aspect that needs to be addressed is students' overreliance on type 1 processing and the missing detection of biases and correction through type 2 processing. Students need to actively reflect on their reasoning and learn strategies to verify their answers. Increasing metacognitive competence with regard to their answering patterns may result in a greater awareness of their intuitive judgments. Shortcut reasoning strategies will always guide our reasoning; we just need to be aware of the advantages and the limitations. The core difference between a powerful and a net misleading shortcut strategy lies in the awareness of what they omit for the sake of simplicity.

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Notes

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