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Exploring Variation in Ways of Thinking About and Acting to Control a Chemical Reaction

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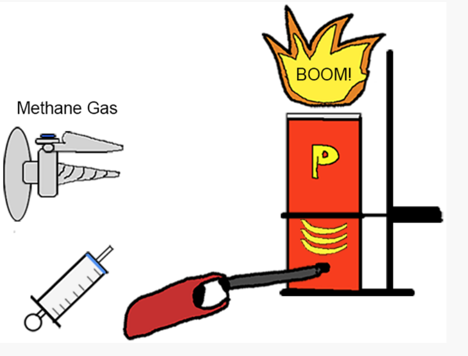
ABSTRACT: Chemical scientists and engineers are interested in controlling chemical processes to attain specific goals, from synthesizing a desired substance to hindering a particular transformation. Nevertheless, students typically have few opportunities to develop the understandings and practices that are required to effectively engage in chemical control. In this study, we investigated similarities and differences among individuals with different levels of expertise in chemistry in the ways they think about how to control and act to control a chemical reaction. Our findings revealed that all types of study participants engage in the manipulation of similar control parameters but with different approaches and purposes. In particular, we observed a shift from a focus on physical to chemical factors, from experienced-based to model-based reasoning, from qualitative to quantitative methods, and from trial-and-error to guided investigation approaches in the thinking and acting of the more novice to the more expert participants in our study.



KEYWORDS: *General Public, Chemical Education Research, Problem Solving/Decision Making*

FEATURE: Chemical Education Research

■ INTRODUCTION

How is chemical change controlled? This is an essential question that chemical thinking allows us to answer,[1] and finding a response in diverse contexts is of vital importance for modern societies. Chemical ideas and practices related to chemical control help us make decisions and implement actions directed at inducing, hindering, and stabilizing chemical change. A well-informed understanding of how to control chemical processes facilitates the design of chemical substances and the elimination or attenuation of undesired reaction pathways. For example, chemists draw upon their understanding of chemical control when determining ways to reduce the concentration of carbon dioxide in the atmosphere and when designing drug treatments to fight human diseases. Other professionals also draw upon their chemical control thinking when strategizing ways to manage a wildfire and when selecting methods for food preservation.

Prior research in chemistry education related to students' understanding of chemical reactions has focused on characterizing how different learners understand these processes,[2−9] but there has been little exploration of students' and experts' understanding of and actual engagement in chemical control. One can expect that novice chemistry learners, more advanced students, and experts in the discipline have different ways of thinking and speaking about chemical control and acting on it. Chemistry is not a homogeneous form of knowing or acting but rather provides multiple ways of seeing and transforming the world.[10] Guided by this hypothesis, this study aims to provide insights into the different ways in which diverse chemistry students and experts think/speak and act when asked to control a chemical reaction during a task designed to uncover these facets of their understanding.

■ LITERATURE REVIEW

Existing research in chemistry and science education indicates that many secondary school students' express a somewhat coherent but alternative conceptual structure when asked to describe and explain changes occurring during chemical reactions.[11] Many of them, for example, implicitly assume that chemical processes need to be initiated by active agents and that chemical reactions always go to completion.[2,3] Novice chemistry students also often assume that the only relevant variables when controlling chemical processes are those that can be manipulated externally, such as temperature and pressure, failing to recognize internal factors such as the molecular structures of reactants and products.[4] Although many learners can correctly identify or define chemical processes and balance chemical equations, they often express confusion about what happens during a chemical change, how

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and why these changes happen, and how they can be controlled.[5] They also tend to make broad generalizations about chemical processes such as believing that all chemical reactions are irreversible, that combustion results in the destruction or disappearance of matter and its mass, or that combustion always produces gaseous compounds.[6,7]

Students' ideas about chemical control are related to their beliefs and understandings about chemical kinetics[12−16] and thermodynamics.[17−22] The research literature in these areas indicates that many students believe that an increase or decrease in the concentration of any reactant in a chemical reaction always leads to a corresponding increase or decrease in the reaction rate.[12,13] One of the anchoring concepts in a content map for general chemistry states that "control of chemical reactions is often not fully accomplished, so details such as limiting reactants and percentage yields are important in characterizing what occurs."[14] Nonetheless, research has shown that students often confuse concepts such as reaction yield and reaction rate.[15,16] Similarly, students frequently do not differentiate among energy-related concepts such as enthalpy, entropy, internal energy, and activation energy and, thus, tend to confuse ideas related to reaction extent versus reaction rate.[19,20] Students' misunderstandings about energy transfer and transformation during chemical processes also affect their thinking about chemical control, as many students frequently think that energy is needed to form bonds and a system releases energy when chemical bonds are broken.[21,22]

■ THEORETICAL FRAMEWORK

Chemical scientists and engineers have developed specific ways of knowing, thinking, and acting that allow them to not only make sense of the material world but also make decisions and take actions to transform it. Chemistry is recognized as a technoscience that leads to the development of knowledge and practices that people can use to extend their abilities and satisfy their needs.[23,24] The chemical thinking framework for teaching and learning chemistry[1] recognizes the technoscientific nature of the discipline and seeks to develop students' ability to use the intellectual and practical tools of chemistry to know, think about, and act on the material world. This framework guides the characterization of learning pathways or progressions[25−27] through which students' ways of thinking and reasoning about chemical synthesis, analysis, and transformation can best develop. These pathways are expected to support the development of students' meaningful understanding of six crosscutting disciplinary concepts that encapsulate major ways of reasoning in chemistry. These crosscutting concepts include *chemical identity*, *structure−property relationships*, *chemical causality*, *chemical mechanism*, *chemical control*, and *benefits-costs-risks*. Each of these concepts provides the basis for addressing essential questions that chemical thinking is well-positioned to answer in a variety of relevant contexts. For example, reasoning about chemical identity guides the answers to questions, such as, what pollutants are present in the air we breathe? Or what nutrients can be found in the foods we eat?

The answers that novices and experts provide to the essential questions identified in the chemical thinking framework are likely to differ both in the conceptual sophistication and the modes of reasoning that are applied.[1] Progression in thinking and acting in this framework is conceived as occurring in a dynamic knowledge space defined by various progress variables. These variables define the dimensions of knowing, thinking, and acting along which progress is most likely to occur.[28] From this perspective, an individual's knowledge and competence in an area is thought of as a dynamic system that changes through interactions with its environment.[29] Over time, these interactions comprise conceptualization processes that may lead to the formation of stable cognitive structures (e.g., concepts, reasoning schemas, action scripts) that gain dominance in an individual's ways of knowing, thinking, and acting in particular contexts. Different dynamic structures may coexist in an individual's mind and become more or less dominant depending on particular experiences or encounters with contextual cues that tend to trigger them. Thus, it is expected that people will express different ways of knowing, thinking, and acting depending not only on their background knowledge, personal experiences and orientations, and level of expertise in a domain but also on the context in which they work and live and the goals of the task they are trying to complete.[30] This perspective shares core assumptions with the conceptual profile theory that recognizes the coexistence of different meanings for the same concept or different ways of thinking and consequently talking about a concept, which are accessed and manifest in different situations.[31,32] Within this theory, thinking and speech are treated as inherently interrelated, and thus, the analysis of different individuals' ways of talking in various contexts is seen as an avenue to uncover different ways of thinking.

■ RESEARCH QUESTIONS

In this study, we used a chemical thinking lens to expand our understanding of students' and experts' reasoning about and approaches to "chemical control" by identifying similarities and differences in their ways of thinking/speaking and acting when asked to control a chemical reaction. In particular, our investigation was guided by the following research questions:

- What similarities and differences exist in the parameters that participants with different levels of expertise in chemistry seek to manipulate to control chemical change?
- What do similarities and differences in ways of thinking/speaking and acting upon different control parameters suggest about key dimensions of progression (progress variables) in the understanding of chemical control?

■ RESEARCH METHODS

Open-ended problems have been shown to provide opportunities for students to express their thinking.[33] Given our interest in exploring different ways of thinking/speaking and doing while controlling chemical reactions, an open-ended activity called "The Exploding Potato Chip Can Design Challenge" was designed to collect data from different sets of participants as described below.

Study Participants

Participants in our study included chemistry students and instructors from a range of educational levels as well as an industrial chemist from the Northeastern United States. In particular, we collected data generated by 12 high school students, 11 undergraduate students taking General Chemistry and Organic Chemistry courses at a highly diverse public university in the area, 2 graduate students at the same university, 2 chemistry professors from the same institution, 4 local public high school chemistry teachers, and one industrial chemist working in the pharmaceutical field. The high school

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students are referred to as "novices" in our study, the undergraduate students are labeled as "intermediate," and the chemistry teachers, professors, and the industrial chemist are considered as "advanced" participants on the basis of their expected understanding of chemical ideas, practices, and ways of thinking. All data collected received the necessary IRB approvals from the school district and from the university. All participants provided informed consent.

Data Collection

The Exploding Potato Chip Can Design Challenge asked participants to imagine that they were part of an engineering team in a company interested in designing a combustion engine that used methane instead of octane. During the testing period, the engineering team was interested in finding the right conditions to produce the biggest explosion possible in a container with a fixed volume. Thus, their challenge was to "*design an explosion with the maximum boom within a container with a fixed volume*" using the materials provided to them (see the Supporting Information). Participants were video and audio recorded as they worked on optimizing the combustion reaction.

The activity was carried out in three different formats, required a laboratory setting, and took 3 h. Some high school students and all undergraduates and graduate students worked in pairs in a single 3 h session where a supervising researcher or teacher asked them to periodically think aloud about their ideas, decisions, and proposed actions. The supervising researcher or teacher made sure to go over the safety protocol verbally with participants, and a section that included clear safety considerations was provided in the worksheet that was shared with all participants (see the Supporting Information). It is important to note that participants engaging with the activity should be warned that, when the explosion occurs and the cap of the potato chip canister is ejected, there is an accompanying sound that may be loud. For that reason, participants should be given the opportunity to request ear protection such as the use of earmuffs prior to engaging with the activity. Some of the high school students completed the task in three different class periods, while participating teachers, professors, and the industrial chemist were given more freedom to complete the work within a 3 h time limit (some of them worked in pairs and others did it individually). Due to the different conditions and group arrangements, the data collected corresponded to five groups of novices, six groups of intermediate participants, and six groups of advanced participants.

In all cases, study participants moved through design cycles, during which they performed a trial, learned from it, and used that information for their next trial. They were encouraged to perform as many trials as they considered necessary to maximize the explosion and to think aloud while engaging in discussions with their group members (or to share their thinking if working alone). Whenever participants were quiet, the researcher intervened by asking think-aloud questions. Table 1 lists the types of think-aloud questions used by the researcher to elicit participants' ideas and reasoning. Additionally, participants were asked to record their ideas, observations, and results in writing on a worksheet that described the challenge and included relevant safety instructions. All written work was collected for the purposes of analysis.

Table 1. Think Aloud Questions used during the Exploding Potato Chip Can Design Challenge

Questions
Could you elaborate more as to why you took this action?
What did you see happening after you performed this action? Why do you think that happened?
Why did you think the action you took worked/did not work?
Is there anything else you would do differently if you performed the same action again?

Data Analysis

The analysis of data involved the observation of all video recordings from the Exploding Potato Chip Can Design Challenge and careful reading of the associated transcripts. This initial analysis was carried out by the first author of this paper in collaboration with six other members of the research group who engaged in peer examination, discussion, and revision of proposed coding categories. Initially, the first author brought transcripts and handouts from the activity to four 2 h research group meetings and asked group members to first individually analyze and then collectively discuss their coding of the data. During these meetings, researchers focused on identifying control parameters and ways of thinking/speaking and acting in which study participants engaged during the activity. These meetings facilitated the identification of direct-control parameters that were actually manipulated (or identified as potential targets) by the participants during the activity (e.g., amount of methane injected into the canister) and indirect-control parameters that included properties of the system that participants wanted to affect (e.g., gas pressure inside the canister).

The second phase of the data analysis focused on generating insights into the different ways in which the various groups of participants thought/spoke and acted while working on the explosion challenge. To attend to this goal, we created a visual map for each transcript and arranged these maps according to their level ("novice" for all high school students, "intermediate" for the undergraduate students, and "advanced" for the graduate students, the high school teachers, the college faculty, and the industrial chemist). Each of the maps captured the initial brainstorming process of that group of participants, highlighted the direct and indirect control parameters that they focused on, and summarized the main ideas, observations, and reflections that participants expressed while working through the activity, as well as the specific sequence of actions in which the group engaged during the task. The analysis of these maps allowed us to identify the different ways of thinking/speaking manifested in each group and the particular actions that were implemented. These analyses were completed by the first and third authors of this paper who individually analyzed each map and then met to discuss until reaching full agreement on the different ways of thinking/speaking and acting manifested by each group during the task. As part of these analyses, the two researchers also individually identified and then jointly agreed on the direct and indirect control parameters that were targeted by each group. Critical reflection about key similarities and differences in the thinking/speaking and acting of different groups of participants was used to identify potential dimensions of progression (progress variables) in the understanding of chemical control.

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RESULTS

The findings from our analysis are summarized in this section where we characterize the types of parameters targeted by different groups of study participants as they sought to control a chemical process and describe major dimensions of progression in their approaches to the task. Our results indicated that (a) most study participants, regardless of their level of expertise, generally manipulated the same direct control parameters and that (b) progression was seen on the extent to which participants paid attention to physical versus chemical factors, relied on experienced-based versus model-based reasoning, used qualitative versus quantitative methods, and took a trial-and-error versus an investigative approach to problem-solving.

Control Parameters

Our analysis revealed that study participants sought to control specific parameters in their attempts to create the largest explosion. The main control parameters manipulated during the activity included the amount of methane in the container, the position of the lighter, the time taken to ignite the gas, and the orientation and movement of the container. The different groups of participants purposefully used these direct-control parameters to affect specific dependent variables in the system (indirect-control parameters), such as the gas pressure, the ratio of methane to oxygen (air) in the system, the amount of certain gas that could escape or enter the container, or the degree of mixing of the gases in the system. Some study participants mentioned or discussed other direct-control parameters that could be targeted but were not actually manipulated due to constraints imposed by the resources and instructions provided. These included the volume of the container, the amount of heat, and the size and number of the holes in the potato chip can (see Table 2).

As can be seen in Table 2, there were no major differences in the types of direct-control parameters mentioned, discussed, and manipulated by groups of participants with different levels of expertise (novice, intermediate, advanced) in our study. There were, however, distinctive ways in which the groups in each of these different levels tended to identify, talk about, and use these direct-control parameters during the activity (representative excerpts from the conversations between different groups of participants are included in Table 3). For example, all groups in our study sought to control the amount of methane gas in the potato chip canister but for different purposes. Most groups at the novice and intermediate levels began varying the amount of CH_4 because they wanted to maximize the gas pressure, compensate for potential gas leakage, or simply produce a larger "boom." A majority of these groups (3/5 novices; 4/6 intermediates) seemed to think that, the more methane gas was in the canister, the larger the explosion. It was not until after some failed trials and reflection that many of these groups recognized that air (oxygen) was needed for the explosion to occur and started to vary the amount of methane to control the O_2 (air) to CH_4 ratio. On the contrary, most groups at the advanced level (4/6) started their work with the clear intent of manipulating this ratio.

Groups at the intermediate level talked about and sought to manipulate the largest number of direct-control and indirect-control parameters. Of all three groups, students at this level were the most likely to express diverse ideas or try to make sense of results using varied pieces of chemical knowledge. For example, 3/5 groups in this category talked about how the different molecular or molar masses of CH_4 and O_2 would affect the location of the corresponding gases within the canister, their rate of diffusion through the container, or their rate of leaking or escaping through holes in the apparatus. Some of these students also related the amount of CH_4 or heat to reaction rate and spontaneity. Groups at this level were also more likely to try to coordinate the effects of different control parameters to maximize the boom. For example, controlling the O_2/CH_4 ratio but also ensuring that the canister and the lighter were in the best position to ensure ignition. Contrastingly, the conversations of students at the novice level were mostly focused on issues related to the control of the amount of methane in the system (in order to, for example, increase the internal pressure, account for gas leaking, and ensure that no CH_4 was left inside the canister when beginning a new trial), while the talk, thinking, and acting of groups at the advanced level tended to be directed at finding and setting the stoichiometric ratio of reactants that would maximize the generation of gaseous products (CO_2).

Table 2. Different Direct-Control and Indirect-Control Parameters Manipulated, Talked about, and Targeted by Different Groups of Study Participants

	Novice	Intermediate	Advanced
Direct-Control Parameters (manipulated)			
Amount of CH_4	5/5	6/6	6/6
Lighter position	2/5	1/6	2/6
Lighter timing	1/5	2/6	
Canister orientation/movement	3/5	2/6	3/6
Direct-Control Parameters (talked about)			
Volume	2/5	1/6	3/6
Heat	2/5	2/6	
Number/size holes		1/6	1/6
Indirect-Control Parameters (targeted)			
Explosion "Boom"	2/5	3/6	1/6
Gas (CH_4) pressure	1/5	3/6	1/6
Gas (CH_4) leakage/escape	2/5	5/6	4/6
O_2 (air)/CH_4 ratio	3/5	5/6	6/6
Gas (CH_4) location		2/6	2/6
Gas (CO_2) pressure			3/6
Reaction rate		2/6	
Reaction spontaneity		1/6	

Major Dimensions of Progression in Approaches to Chemical Control

Through our analysis, we identified four major dimensions of progression in which the approaches followed by different groups of participants to confront the explosion challenge seemed to progress from novice to intermediate to advanced levels. These dimensions of progression were labeled: *Physical to chemical factors*, *experience-based to model-based reasoning*, *qualitative to quantitative methods*, and *trial-and-error to guided investigation in problem solving*.

Physical to Chemical Factors. Even though all groups of participants focused on controlling similar parameters and engaged in similar ways of doing to induce an explosion, their ways of thinking/speaking were quite distinctive. Groups at the novice level tended to focus their conversations on the control and manipulation of physical factors. For example, their initial focus of attention was on issues related to equipment characteristics and setup (e.g., volume and position of the canister, how to inject the gas), and their thoughts during the

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Table 3. Excerpts used by Novice, Intermediate, and Advanced Participants When Brainstorming about and Deciding What Parameters to Control

Novice
Definitely the amount of methane gas we put in it (is what matters) because it increases the boom by a lot because if you have higher amount it causes to boom more.
Intermediate
I think we should put an amount, the more gas you have, the bigger the flame and I do not think the flame is gonna come out but it is gonna push the lid off, you know? If you put more (methane) gas in there, as opposed to like a small amount.
Advanced
All right, well, stoichiometric combustion, which does not really happen, but you take methane, it reacts with oxygen. I would guess you'd want slight excess of methane, not that you would be able to calculate exactly how much methane to inject to react with all the oxygen and sustain it. I could probably give a ballpark estimate.

Table 4. Ways of Speaking That Illustrate Participants' Shift from Physical Factors (novice) Towards Chemical Factors (advanced)

Novice
So, let us try 60 mL (of methane) again but let us try to get it doubled fast to see if that makes a difference, ok the difference is based on how long you take to put it in, I guess the methane escaped the first time.
Intermediate
Um so methane combined. . .well in all combustion reactions, you have to um CO_2 is a product. But then you have to actually heat. So, heat was introduced to methane and normally when adding heat to something, it always increases the rate at which the reaction will occur. So, whatever, the product was, the CO_2 or whatever gas came out was very spontaneous.
Advanced
So clearly, we built up pressure and we made a pretty big expansion. The pressure increased too much, and it happened relatively quickly so that the top flew off. So, it would be interesting to calculate, you know let us say it is just pure methane which I do not think it is because there are other things in there, too. But let us say it is pure methane, what the change in moles of gas would be? Assuming that it is an ideal gas and the pressure [pause] then we are clearly making more moles of $CO_2$and H_2O than we had methane and O_2,that has to be the case otherwise we would not have a pressure built up.

activity were directed at either how to control the amount of CH_4 in the canister (by adding it, preventing it from escaping, or removing it from the container) or ensuring a good contact between methane gas and the lighter flame. Although most of these students at some point during the task recognized that air (oxygen) was needed for the explosion to occur, only one of the groups made an explicit reference to a chemical reaction taking place in the system and wrote down the corresponding chemical equation.

Analysis of the conversations between students in groups at the intermediate level revealed a more explicit awareness of the existence of a chemical reaction. Some students referred to the process as combustion while others talked about the effect of different parameters on reaction rate and spontaneity. Some of these students also paid attention to distinctive properties of the substances in the system (e.g., molar or molecular mass, density) that affected their physical behavior (location in the container, rate of diffusion or escape). Despite these greater attention to chemical factors, none of these groups referred to or explicitly wrote down the chemical equation for the process of combustion. This is in contrast with the approach followed by almost all groups (5/6) at the advanced level who, early during the activity, wrote down the chemical equation for the reaction and used it to guide their thinking and actions. These are also the only groups that recognized that the boom of the explosion was related to the pressure generated by the gaseous products (CO_2) of the reaction, while many groups at other levels seemed to associate the boom with the pressure of methane in the system. Representative excerpts from participants' conversations that illustrate the progression from a focus on physical to chemical factors are included in Table 4.

Experience-Based to Model-Based Reasoning. Analysis of similarities and differences in the ways of speaking/talking of different groups of participants, as illustrated in Tables 3 and 4, revealed a shift in reasoning from more heavily based on personal experiences with objects and processes to more explicitly guided by scientific models of the system and its components. Groups of students at the novice level tended to more frequently change direct parameters guided by experiential knowledge about gases and explosions (e.g., an explosion is likely to be larger the more gas you have, and the more compressed the gas is, gases can leak from containers; air is needed for something to burn). Although students at the intermediate level also manifested this way of reasoning, they were more likely to express ideas that were guided by physical and chemical models. For example, they more often referred to the presence of different submicroscopic particles with properties (e.g., mass) that were expected to affect their behavior (e.g., their distribution inside the can, their rate of diffusion). They also articulated model-based ideas about how heat or the amount of substance could affect the reaction rate. Finally, most groups of participants at the advanced level began their analysis by articulating and symbolically representing a chemical model for the combustion reaction that they expected to take place inside the can and then used this model to guide their thinking and actions.

Qualitative to Quantitative Methods. Participants working on the Exploding Potato Chip Can Design Challenge engaged in both qualitative and quantitative ways of thinking during the task. However, a qualitative approach was used more often by novice (4/5) and intermediate (5/6) groups while participants at the advanced level engaged more often (4/6) in quantitative ways of thinking. Students in novice

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Table 5. Ways of Speaking That Illustrate Novice Participants Using Qualitative Reasoning, Intermediate Participants Incorporating Elements of Quantitative Reasoning, and Advanced Participants Using Primarily Quantitative Reasoning

Novice

I think we should have added less methane because we noticed like during the practice, the first time when we put less methane it exploded but then after that we kind of thinking cause it exploded big so we thought if we put more gas then it would explode big cause like if you see fire and gas, gas causes fire so we thought, if we put more gas that fire would be, I mean the explosion would get bigger but it did not even explode.

Intermediate

O: I cannot remember for the life of me which weighs more, air or methane. Do you have any ideas about that?

F: The only thing I could say is that methane has carbon in it. So, I'd say

O: Yeah, it has one carbon in it.

F: Right, so I'd say it would weigh more, since it is not just

O: Yeah, but what is an air molecule? Cause air is not homogeneous. It is a mixture of oxygen. Wait okay, I'm done. A carbon molecule is approximately what, 12 AMUs? Plus 4 AMUs for the four hydrogens around it and then the oxygen molecule is two oxygen atoms. Oxygen has a molecular weight of 16.

F: Yeah, so that is heavier.

Advanced

Alright well stoichiometric combustion, which does not really happen, but you take methane which reacts with oxygen ideally you produce CO_2 and water. . .I just need to know it is about two inches, five centimeters. So that is yeah, we will call it five centimeters. So that is 75 times, let us call it 410, so 750 cubic centimeters. Close enough to a liter. I'll call it a liter. A mole of air occupies close enough to 20 L. So, it is a 20th of a mole, and then only a 5th of that is oxygen. I am going to pretend that nitrogen plays no part in this. So, a fifth of a 20th is 100, is 100th so we've got.01 mol of oxygen reacting with methane, and the balance is ahead. So CH_4 plus − I am trying to balance this reaction in my head.

Table 6. Characteristic Ways of Speaking Used by Participants That Illustrate a Shift from a Trial-and-Error Approach (novice) to Guided Investigation (advanced)

Novice

S1: You wanna try like half of that?

S2: Yeah

S1: 30 this time. Ok yeah we did it right but it did not like pop off

S2: It did not ignite

S1: Yeah

S2: So maybe, maybe it is just too little (methane)

S2: cause I definitely saw a flame in there it did ignite

S1: yeah ok, ok 60 we got an explosion

S2: 30 we did not

S2: wanna try like

S1: 90 maybe?

Intermediate

F: Intriguing! Let us try 45.

O: Okay that pump is hot.

F: Oof. Okay, 45 worked. Let us try, so somewhere between 45 and 50 is where the cutoff point is.

O: The rate at which you let the gas out will also determine how much gas you suck up in the syringe.

Advanced

There is some sort of ratio situation, but we will find out. Because this is a closed system. It is a fixed volume. The only variable is really how much methane you are putting in or not putting in. So, you would imagine that the question is telling you that there is an ideal amount in this fixed volume that will give you a boom. Cause then it would be kind of foolish to have you experiment like this. But I guess it is kind of what you have to do, right, when you are in a real-life situation when you do not know that there's an ideal way to do something you just have to run the experiment over and over and over again. If you always get the same result, then there is not an ideal way to do it. So, I guess the question is, do these people know something?

groups, for example, commonly talked about adding more or less methane into the canister, but their choices of amounts were not guided by any specific calculations (except in one case that a group at this level estimated the volume of the can). Some groups altered the time they waited to insert the lighter into canister after filling it up with methane, but again their rationales did not go beyond waiting more or less time. Most participants in this category recognized that there might be a specific O_2 (air)/CH_4 ratio that would maximize the explosion, but only one group in this set attempted to determine the actual value on the basis of the chemical equation.

The reasoning of students in groups at the intermediate level was also mostly qualitative, but there were more instances of quantitative thinking. Some of these groups, for example, engaged in the calculation of the molecular or molar masses of methane and oxygen and used these results to compare their relative densities or diffusion rates. In contrast, a majority of the participants at the advanced level started their work trying to figure out the stoichiometric O_2/CH_4 ratio on the basis of the chemical equation for the combustion reaction and a few of them also sought to estimate the volume of the container. Then, they used these results to guide their decisions about how much methane gas to add to the canister. Representative excerpts from participants' conversations that illustrate their different qualitative and quantitative approaches are included in Table 5.

Trial-and-error to guided investigation problem-solving. Although most groups in our study relied on trial-

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and-error to address the challenge rather than on systematic investigation, attempts to systematicity and guided exploration were more frequently observed in moving from novice to intermediate to advanced groups. Most groups at the novice level (4/5) followed a trial-and-error approach in which the results of a given attempt to generate an explosion were used to guide the changes made in the subsequent trial. Conversations and reflection after each trial often brought new ideas to be tested, but most groups did not follow a systematic plan of action.

In general, groups at the intermediate level also engaged in trial-and-error, but there were more instances of students engaging in the systematic analysis of the changes induced by a single variable (e.g., search for the optimal O_2/CH_4 volume ratio) or explicit attempts to control for changes in several variables (e.g., amount of CH_4 injected, orientation of the canister, and location of the lighter). As mentioned before, a majority of the groups at the advanced level took some time before engaging in action to analyze the stoichiometry of the combustion reaction and the characteristics of the experimental setup (e.g., canister volume) and used these results to guide the decisions they made and the actions that were implemented. Nevertheless, these groups also engaged in trial-and-error particularly when they encountered unexpected results from an attempt to make an explosion. Representative excerpts from participants' conversations that illustrate their different approaches to problem solving are included in Table 6.

DISCUSSION

The central goal of our study was to explore how individuals with different levels of expertise in chemistry think/speak and act when asked to engage in an activity designed to explore their approaches to chemical control. In general, all types of groups (novice, intermediate, advanced) engaged in the manipulation of the same direct-control parameters as summarized in Table 2 but with somewhat different approaches and purposes. The most novice participants mostly paid attention to and sought to affect physical factors (e.g., internal gas pressure, gas leakage) using experience-based reasoning and following a qualitative trial-and-error approach. On the contrary, the most advanced participants mostly focused their efforts on affecting a single chemical factor (O_2/CH_4 ratio) in a more investigative manner using model-based reasoning and knowledge about the stoichiometry of the chemical reaction to guide their tests. Students at the intermediate level expressed the most diverse set of ideas and considered the largest number of variables to manipulate and affect, with more frequent attempts of model-based and quantitative reasoning and systematic testing than students in the novice groups but still omitting important qualitative and quantitative features of the targeted chemical process.

Although to various extents and at different moments during the activity, all groups of participants engaged in trial-and-error when seeking conditions that could lead to the strongest or loudest explosion. In doing so, participants engaged in the manipulation of one or more variables intending to produce the desired outcome without a well-founded or well-formulated rationale for their actions. Other authors have referred to this approach as an "engineering model" of experimentation,[34] in contrast to a "scientific model" that seeks to establish cause−effect relations between variables by systematically investigating the effect of each relevant variable while holding the others constant. Existing research suggests that the prevalence of the engineering model in the approach followed by most groups of participants at the novice and intermediate levels in our study may have been influenced by two main factors. The knowledge base of participating students and the nature of the task. Engaging in scientific reasoning requires a basic level of both content knowledge and metacognitive knowledge that our more novice participants did not have proficiency in or did not activate as they faced the challenge.[35] On the contrary, tasks that point toward a desired outcome (e.g., making the loudest explosion) are known to favor the application of an engineering model.[34]

Despite observed differences in the ways of speaking/thinking and acting among the various groups at each level of expertise, our analysis revealed four distinctive dimensions of progress in reasoning about and effecting chemical control. There were clear shifts in the nature of the variables that participants wanted to influence, from physical to chemical, the type of reasoning applied, from experience-based to model-based and from qualitative to more quantitative, and the approach to problem-solving, from trial-and-error to guided investigation. The latter three types of shifts have been observed in groups of students who are invited to engage in scaffolded inquiry tasks for extended periods of time, receive formative feedback, and are encouraged to reflect on their decisions and the results of their actions.[36]

LIMITATIONS

Our results emerged from the analysis of the different ways of thinking/speaking and acting of a small number of participants at each level of expertise working on a single chemical control task. Consequently, one should be cautious with the generalizability of our findings. Additional investigations with a larger and more diverse set of participants working on various activities are needed to determine the extent to which the dimensions of variation and progress that were identified manifest in various contexts.

IMPLICATIONS

The success of our study participants in generating an explosion with a large boom did not seem to correlate with a particular approach to chemical control. Groups that engaged in trial-and-error used experience-based and qualitative reasoning and focused on physical factors were as able to produce an explosion as groups that used chemical ideas and models to guide their work and applied more quantitative reasoning. Nevertheless, the latter types of groups often needed less time to identify the direct and indirect control parameters that were most productive for successfully completing the task. These groups included individuals with expected higher levels of knowledge and experience in chemistry. Nevertheless, our study suggests that students at the novice and intermediate stages can productively engage in thinking and acting on chemical control if given the opportunity and time to work in these types of problems in an active and reflective manner. Chemistry instructors at all educational levels should thus create more spaces for students to engage in the design, implementation, and evaluation of different methods to control a variety of chemical processes.

The majority of the tasks that chemistry students tend to confront in conventional chemistry courses ask them to verify an expected outcome, reproduce a procedure, and, occasion-

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ally, investigate and make sense of a phenomenon. Despite the fact that a central activity of chemistry is the design and evaluation of processes to achieve a desired outcome (e.g., synthesizing a particular substance, inducing or hindering a specific transformation), most chemistry curricula do not support the development of the ways of thinking and acting that are needed to effectively address these types of challenges. Our results suggest that students have conceptual resources that support productive engagement in chemical control design tasks but would benefit from more opportunities to do so while receiving formative feedback that presses them to shift their attention from physical to chemical factors, from reasoning based on concrete objects and experiences to model-based reasoning, from qualitative to quantitative methods, and from a trial-and-error to guided investigation approaches.

Our findings provide insights into four potential progress variables that need to be considered when building a learning progression[25−27] for the core crosscutting concept of chemical control. The identification of likely dimensions of progression is critical for the development of curricular sequences, learning tasks, and assessment tools that can better scaffold student learning in this area. Our results support the perspective that progression in reasoning about chemical control and acting to control a chemical process does not necessarily imply the complete substitution of some ways of thinking and acting by others but rather the acquisition of an enriched set of cognitive tools and the ability to deploy them in more productive manners in particular contexts.[29,30] This suggests that it would be productive to create more opportunities for students to engage in metacognitive reflection to recognize what they already know and evaluate what conceptual resources and reasoning strategies may be more appropriate depending on the nature of the task at hand.

Researchers and philosophers have pointed out that chemistry is not a monolithic way of thinking, but it provides diverse ways of seeing the world.[10] From a sociocultural perspective, different ways of speaking, thinking, and acting can be recognized and claimed to be valuable in different situations. In the conceptual profile theory,[31,32] the different ways of thinking about a concept define a specific zone in its profile and need to be characterized by exploring three different domains: (1) the sociocultural domain that elicits how a concept developed through the history of mankind; (2) the ontogenetic domain that elicits how the concept of interest is learned by different individuals; and (3) the microgenetic domain that elicits how a concept is built and understood through moment to moment interactions in various contexts. The study presented here can be situated in the microgenetic domain, and it begins to shed light on different zones in the conceptual profile for "chemical control." Nevertheless, additional investigations involving a larger and more diverse set of participants working on different contexts are needed to fully characterize such a conceptual profile and to explore how this understanding can be used by instructors to better support and scaffold learning in this area.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00902.

Exploding Potato Chip Can Design Challenge worksheet provided to participants (PDF)

Exploding Potato Chip Can Design Challenge safety considerations for teachers (PDF)

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Notes

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■ REFERENCES

(1) Sevian, H.; Talanquer, V. Rethinking Chemistry: A Learning Progression on Chemical Thinking. *Chem. Educ. Res. Pract.* **2014**, *15* (1), 10−23.

(2) Johnson, P. Children's Understanding of Substances, Part 2: Explaining Chemical Change. *Int. J. Sci. Educ.* **2002**, *24* (10), 1037−1054.

(3) Taber, K. S.; García-Franco, A. Learning Processes in Chemistry: Drawing upon Cognitive Resources to Learn about the Particulate Structure of Matter. *J. Learn. Sci.* **2010**, *19* (1), 99−142.

(4) Kind, V. *Beyond Appearances: Students' Misconceptions about Basic Chemical Ideas*; Durham University, 2004; pp 1−84.

(5) Hesse, J. J.; Anderson, C. W. Students' Conceptions of Chemical Change. *J. Res. Sci. Teach.* **1992**, *29* (3), 277−299.

(6) Boujaoude, S. B. A Study of the Nature of Students' Understandings about the Concept of Burning. *J. Res. Sci. Teach.* **1991**, *28* (8), 689−704.

(7) Nakhleh, M. B. Why Some Students Don't Learn Chemistry: Chemical Misconceptions. *J. Chem. Educ.* **1992**, *69* (3), 191−196.

(8) Van Driel, J. H.; De Vos, W.; Verloop, N.; Dekkers, H. Developing Secondary Students' Conceptions of Chemical Reactions: The Introduction of Chemical Equilibrium. *Int. J. Sci. Educ.* **1998**, *20* (4), 379−392.

(9) Solomonidou, C.; Stavridou, H. From Inert Object to Chemical Substance: Students' Initial Conceptions and Conceptual Development during an Introductory Experimental Chemistry Sequence. *Sci. Educ.* **2000**, *84* (3), 382−400.

(10) Freire, M.; Talanquer, V.; Amaral, E. Conceptual Profile of Chemistry: A Framework for Enriching Thinking and Action in Chemistry Education. *Int. J. Sci. Educ.* **2019**, *41* (5), 674−692.

(11) Chandrasegaran, A. L.; Treagust, D. F.; Mocerino, M. The Development of a Two-Tier Multiple-Choice Diagnostic Instrument for Evaluating Secondary School Students' Ability to Describe and Explain Chemical Reactions Using Multiple Levels of Representation. *Chem. Educ. Res. Pract.* **2007**, *8* (3), 293−307.

(12) Tačtan, Ö.; Boz, Y. Cooperative Learning Instruction for Conceptual Change in the Concepts of Chemical Kinetics. *Chem. Educ. Res. Pract.* **2012**, *13*, 221−236.

(13) Van Driel, J. H. Students' Corpuscular Conceptions in the Context of Chemical Equillibrium and Chemical Kinetics. *Chem. Educ. Res. Pract.* **2002**, *3* (2), 201−213.

(14) Holme, T.; Luxford, C.; Murphy, K. Updating the General Chemistry Anchoring Concepts Content Map. *J. Chem. Educ.* **2015**, *92* (6), 1115−1116.

(15) Kousathana, M.; Tsaparlis, G. Students' Errors in Solving Numerical Chemical-Equilibrium Problems. *Chem. Educ. Res. Pract.* **2002**, *3* (1), 5−17.

(16) Yalçinkaya, E.; Tačtan-Kirik, Ö.; Boz, Y.; Yildiran, D. Is Case-Based Learning an Effective Teaching Strategy to Challenge Students' Alternative Conceptions Regarding Chemical Kinetics? *Res. Sci. Technol. Educ.* **2012**, *30* (2), 151−172.

(17) Tsaparlis, G.; Finlayson, O. E. Physical Chemistry Education: Its Multiple Facets and Aspects. *Chem. Educ. Res. Pract.* **2014**, *15*, 257−265.

(18) Wolfson, A. J.; Rowland, S. L.; Lawrie, G. A.; Wright, A. H. Student Conceptions About Energy Transformations: Progression from General Chemistry to Biochemistry. *Chem. Educ. Res. Pract.* **2014**, *15*, 168−183.

(19) Bain, K.; Moon, A.; Mack, M. R.; Towns, M. H. A Review of Research in the Teaching and Learning of Thermodynamics at the University Level. *Chem. Edu. Res. Pract.* **2014**, *15* (3), 320−335.

(20) Van Roon, H. F.; Van Sprang, H. F.; Verdonk, A. H. 'Work' and 'Heat': On a Road Towards Thermodynamics. *Int. J. Sci. Educ.* **1994**, *16* (2), 131−144.

(21) Greenbowe, T. J.; Meltzer, D. E. Student Learning of Thermochemical Concepts in the Context of Solution Calorimetry. *Int. J. Sci. Educ.* **2003**, *25* (7), 779−800.

(22) Galley, W. C. Exothermic Bond Breaking: A Persistent Misconception. *J. Chem. Educ.* **2004**, *81* (4), 523−525.

(23) Dugger, W. E. Standards for Technological Literacy. *Phi Delta Kappan* **2001**, *82* (7), 513.

(24) Talanquer, V. School Chemistry: The Need for Transgression. *Sci. Educ.* **2013**, *22* (7), 1757−1773.

(25) Duschl, R.; Maeng, S.; Sezen, A. Learning Progressions and Teaching Sequences: A Review and Analysis. *Stud. Sci. Educ.* **2011**, *47* (2), 123−182.

(26) Corcoran, T.; Mosher, F. A.; Rogat, A. *Learning Progressions in Science: An Evidence-Based Approach to Reform. CPRE Research Report # RR-63*; Consortium for Policy Research in Education, 2009.

(27) Smith, C. L.; Wiser, M.; Anderson, C. W.; Krajcik, J. FOCUS ARTICLE: Implications of Research on Children's Learning for Standards and Assessment: A Proposed Learning Progression for Matter and the Atomic-Molecular Theory. *Meas. Interdiscip. Res. Perspect.* **2006**, *4* (1−2), 1−98.

(28) Wilson, M. Measuring Progression: Assessment Structures Underlying a Learning Progression. *J. Res. Sci. Teach.* **2009**, *46*, 716−730.

(29) Brown, D. E.; Hammer, D. Conceptual Change in Physics. In *International Handbook of Research on Conceptual Change*; Vosniadou, S., Ed.; Routledge: New York, 2008; pp 127−154.

(30) Siegler, R. S. *Emerging Minds: The Process of Change in Children's Thinking*; Oxford University Press: New York, NY, 1996.

(31) Mortimer, E. F.; El-Hani, C. N. *Conceptual Profiles: A Theory of Teaching and Learning Scientific Concepts*; Springer: Dordrecht, The Netherlands, 2014.

(32) Orduña Picón, R.; Sevian, H.; Mortimer, E. F. Conceptual Profile of Substance. *Sci. Educ.* **2020**, *29* (5), 1317−1360.

(33) Overton, T. L.; Potter, N. M. Investigating Students' Success in Solving and Attitudes towards Context-Rich Open-Ended Problems in Chemistry. *Chem. Educ. Res. Pract.* **2011**, *12* (3), 294−302.

(34) Schauble, L.; Klopfer, L. E.; Raghavan, K. Students' Transition from an Engineering Model to a Science Model of Experimentation. *J. Res. Sci. Teach.* **1991**, *28* (9), 859−882.

(35) Kuhn, D.; Black, J.; Keselman, A.; Kaplan, D. The Development of Cognitive Skills to Support Inquiry Learning. *Cogn. Instr.* **2000**, *18* (4), 495−523.

(36) Schauble, L.; Glaser, R. Scientific Thinking in Children and Adults. *Cont. Hum. Dev.* **1990**, *21*, 9−26.

https://doi.org/10.1021/acs.jchemed.1c00902
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