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Insights into How Students Learn the Difference between a Weak Acid and a Strong Acid from Cartoon Tutorials Employing Visualizations

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ABSTRACT: This article summarizes an investigation into how Flash-based cartoon video tutorials featuring molecular visualizations affect students' mental models of acetic acid and hydrochloric acid solutions and how the acids respond when tested for electrical conductance. Variation theory served as the theoretical framework for examining how students compared and contrasted their understanding of weak and strong acids to the tutorials. Specifically, students' ability to recognize variation between their mental models and the events portrayed in the videos was examined through picture construction exercises and semistructured interview questions focused on metacognitive monitoring. Interestingly, the items noticed as being in variance were items that were emphasized by still image representation in the tutorials prior to showing the visualizations. Mechanistic items, specifically movement of ionic species toward electrodes, were replicated in students' drawings only if they were explicitly conveyed, but students were not inclined to mention them as features in variance with their initial understanding. Overall, scaffolding animations in a cartoon context with explicit connections between experimental evidence and the submicroscopic level resulted in students being proficient at replicating what they explicitly observed both structurally and mechanistically.

KEYWORDS: *First-Year Undergraduate/General, High-School/Introductory Chemistry, Chemical Education Research, Computer-Based Learning, Misconceptions/Discrepant Events, Acids/Bases, Electrochemistry, Qualitative Analysis, Solutions/Solvents*

FEATURE: Chemical Education Research

INTRODUCTION

This study is part of a larger study, of which the first part was published in 2014.[1] In Part I, variation theory was used to examine how students detected differences between their understanding and the information presented in 15 molecular visualizations of pure liquid water and solid and aqueous sodium chloride tested for electrical conduction.[1] The findings of this study revealed that students made significant progress toward improving their mental models of the animated events after viewing the molecular visualizations as they tended to incorporate aspects of the visualizations in which they identified variance from their mental model. Students often demonstrated imperfect understanding and had difficulty adapting their understanding to completely match what they saw. Metacognitive monitoring and mental model picture construction exercises revealed that students were most likely to correct their understanding to fit with basic structural features portrayed in the animations, but students tended to dismiss details of the animations that were too challenging to draw or would take too much effort to construct. The visualizations, in part I, were not part of a lesson, and lacked the guidance that comes from instruction.

Tutorials Featuring Molecular Visualizations

In part II of this study, we turn our attention toward studying how students learn from visualizations that are introduced in the context of an animated video lesson, which we also refer to as a tutorial due to their intended use. They were designed to guide and assist students with making connections between macroscopic evidence and submicroscopic representations. Online tutorials, tutorial video clips and interdisciplinary, application-based tutorials that were introduced to cover general chemistry principles have all been shown to improve chemistry students' test performance when used to supplement chemistry instruction.[2−4] Video tutoring has the advantage of offering valuable and convenient assistance at low cost and, more importantly, helps students, particularly average and low-achieving students, to master content and improve problem solving performance.[3] In our study, tutorials were uniquely used to scaffold and introduce visualizations allowing key structural representations from the visualization to be emphasized.

Many researchers have shown that molecular visualizations are useful tools that aid students in the conceptualization of the particulate nature of macroscopic events.[5−15] Viewing animations helps students to form a more detailed mental model of the event,[1] and helps students connect to concrete models.[16] However, even though students may try to adapt what they see in the animations, they typically retain imperfect understanding.[1] For students to learn from external representations, they must have the cognitive ability to reason and think about the concepts being represented. In essence, students need cognitive skills that are necessary for understanding the purpose of the animation to help them become visually literate of the information portrayed.[16] Studies have also shown that when an animation is complex it can lead to further difficulties as students

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may misinterpret what they view.[17] Complex animations without scaffolding may overwhelm students and affect their ability to process the visuals.

It is important for students to have guidance and instruction while viewing molecular visualizations as students may miss essential features if they are not made explicit through instruction.[5,18] Chang and Linn reported that guiding students to make connections to laboratory events, such as critiquing confounding experiments and conducting virtual experiments, while also considering the information presented in molecular visualizations related to the events, helped students make connections between macroscopic and atomic levels.[19] But none of these studies have examined how scaffolding complex animations through an animated lesson context taught by a cartoon tutor affects student learning. This is important to study as many instructors are striving to flip their classrooms with video-recorded lectures, which are similar in passivity to these scaffolded tutorials with the expectation that they will prepare students to enter the classroom to focus on higher-level collaborative exercises. Thus, the goal of this study was to examine how students adapted their mental models of a strong acid [aqueous hydrochloric acid] and a weak acid [aqueous acetic acid] tested for electrical conductivity, to fit with features of the same events portrayed in video tutorials.

Studies on Students' Understanding of Acids

Understanding how students tend to make sense of the nature of acidic aqueous solutions is important as it allows us better insight into how the videos affect student understanding. Since the students in this study had very little instruction about acids, prior knowledge was likely strongly influential, and these ideas are often contrary to those of scientists.[20,21]

A common introductory definition of acidity is the Arrhenius definition, a concrete model that focuses on matter[21,22] and recognizes that acids produce hydrogen ions in aqueous solution. The Brønsted-Lowry and Lewis theories are also commonly referenced definitions that describe acids with bases in the context of reactions.[22] These process models are less relevant to this study, as reactions were not the focus of the videos. Instead the videos in this study portrayed a materialistic view of acids, consistent with the Arrhenius definition, in which a strong acid dissociates readily into hydrogen ions and anions, while a weak acid dissociates much less.[21,22] This definition, while seemingly concrete, can be problematic for students when they are asked to apply it to classify acidic solutions as strongly acidic or weakly acidic.[23] Some students misunderstand the importance of holding the concentrations constant so that comparisons can be made as to how readily the acids dissociate into ions. In addition, students may think that a strong acid has a strong bond causing it to stay together, while a weak acid has a weak bond that is easily broken.[23,24] To summarize, it seems that many students struggle to understand the ionic nature of acids[20,21] which could affect students' ability to relate how acidic solutions would have the ability to conduct electricity.

Understanding acids and acid strength continues to be challenging for students as they progress into advanced college chemistry courses. McClary and Talanquer reported that advanced college chemistry students' mental models of acids were often hybrid models that combined assumptions from one or more scientific models and were partnered with intuitive beliefs about chemical properties.[25] In this paper, we examine how general chemistry students begin to construct their knowledge in the direction of their abilities and experiences and refine their understanding with the assistance of tutorials featuring molecular visualizations.

■ METHODOLOGY

Theoretical Framework: Variation Theory

The primary purpose of the study was to determine how students made sense of the information presented in tutorials that focused on the particulate nature of strong and weak acids. Specifically, what features do students pay attention to when they view tutorials and how does this affect their understanding. Variation theory, a theoretical extension of phenomenography, was the theoretical framework used to conceptualize the study and to examine the findings. For a more detailed explanation of variation theory, we encourage the reader to review the paper associated with part I of this study.[1] In short, variation theory is a lens that aims to understand how students create a meaningful conception by discerning how a phenomenon changes as it progresses and what aspects of the changing phenomenon contrast with their own understanding.[26] When learners experience variation, they modify their understanding to better fit with the aspects initially in variance to their own. In this study, we explored the specific tutorial features that students recognized as similar to and different from their initial understanding. Specifically, the participants' understanding of the conceptual nature of a weak and strong acid as related to the acids' ability to conduct electricity was investigated before and after students viewed the tutorials to discern those variation aspects that motivated change. The novelty of this study is that it examines how students learn from animations that are presented in a cartoon story context, in which an animated tutor scaffolds the learning experience.

The constructs that were used to explore how students recognized variation were mental models and metacognition, which was consistent with the constructs used in Part I of the study.[1] The mental model construct refers to how one mentally pictures structural, behavioral or functional behaviors of a real or imaginary object, process, event, or in this case, the chemical phenomena of electrical conduction involving strong and weak acids.[1,27] To reveal students' mental models of these events, click and drag constructions and oral descriptions of picture constructions made prior to viewing the tutorials were examined. At the end of the study, after students viewed the tutorials, they were allowed to embellish their picture constructions with hand drawn changes that they also orally described. The drawings gave insight into the aspects of the video features that students recognized as being at variance with the way they initially represented the phenomenon. The oral descriptions and interviews allowed us to delve into the mechanistic aspects that students may find challenging to represent through pictures. The second construct, metacognition through a monitoring exercise, was utilized to have students explicitly address how features portrayed in the tutorials were new to them and the aspects that were familiar to them. This revealed students' perception of what they attended to and what they filtered out in order to create a meaningful conception. Together, these constructs revealed how students viewed their understanding as varying from the tutorials and the kinds of changes they were willing to make to modify their initial explanations to be consistent with what they learned.

Research Questions

The main goal of this study was to examine how students identified variation between their mental models and the critical

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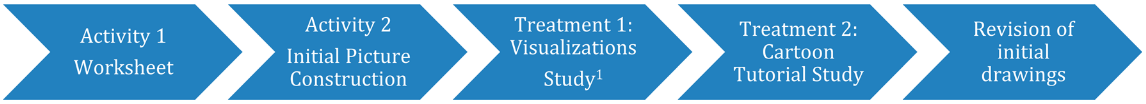


Figure 1. Sequence of events involved in the study.[1]

features portrayed in the video tutorials. The following research questions guided the study.

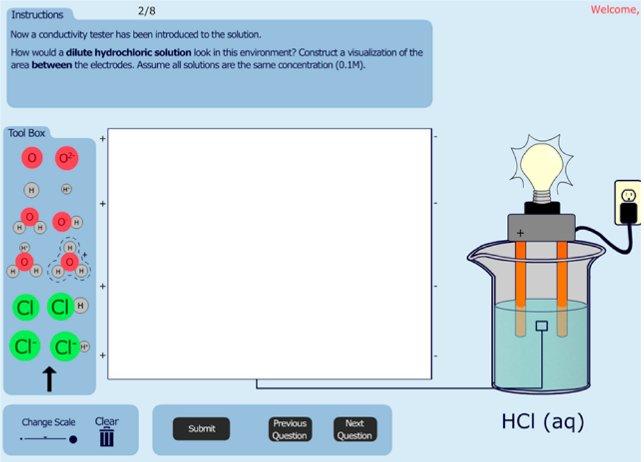
1. What kinds of information portrayed in cartoon tutorials do students identify as new or familiar to their mental models?
2. How do they express modification to their mental models through pictorial construction and oral descriptions?

Research Design

In the spring of 2012, 24 ethnically diverse students consisting of 11 males and 13 females enrolled in a first-semester, introductory chemistry course were invited to participate in an Institutional Review Board (IRB) approved study. An oral announcement was made and all students who expressed interest were invited to participate and awarded extra credit by their instructor who also provided alternative extra credit options for students unable to participate. The study reported in this manuscript was conducted as part of a larger study and according to the following sequence (Figure 1). First, they completed two activities: a worksheet and a picture construction exercise. Next, students were shown 15 molecular visualizations (Treatment 1) that depicted how pure water, solid sodium chloride, and aqueous sodium chloride responded when tested for electrical conductivity. Following Treatment 1, the students were shown four cartoon tutorials to learn how a conductivity tester works, how strong and weak acid solutions respond to conductivity tests, and how these processes can be represented symbolically (Treatment 2). The study ended with a drawing task to examine how students' mental models changed with regard to their particulate level understanding of the substances initially introduced.

Activities 1 and 2. The first and second activities were conducted to examine students' prior knowledge of the concepts. Students completed a worksheet in which they predicted whether the chemicals: solid sodium chloride, aqueous sodium chloride, aqueous hydrochloric acid, and aqueous acetic acid, represented by their chemical formulas, would conduct or not, and then they were asked to explain the reason behind their prediction. For the second activity, students made atomic level pictures of the same chemicals that were introduced in the worksheet as they were tested for electrical conduction. The pictures were constructed using click and drag electronic tools in which students were presented with an artistic rendition of the macroscopic event connected to a blank box for depicting how they mentally pictured the submicroscopic nature of the macroscopic events. The tool contained a "tool box" that housed a variety of atomic level representations of varying appropriateness that the students could use to make their representations (Figure 2). It is important to notice that an arrow was included as an option for students to select to help with conveying the mechanism of the reaction and how movement would occur. Students were also interviewed to further delve into what their pictures conveyed about their understanding.

Treatment 1: Molecular Visualizations Study. Following the two activities, students were shown 15 very short, molecular visualizations, each less than 30 s, of solid and aqueous sodium chloride (at varying complexities) and pure water tested for electrical conductivity. The animations did not have narration nor did they have an instructional context to scaffold the animations. The students were asked to metacognitively monitor how the animations were similar to or different from how they mentally pictured the events, which was the focus of Part I of this study.[1] (Some of the tutorials and animations described in this manuscript may be accessed online at the Chemteam.net Web site;[29] all the tutorials can be accessed on YouTube.[30])


Instructions 2/8

Now a conductivity tester has been introduced to the solution.

How would a **dilute hydrochloric solution** look in this environment? Construct a visualization of the area **between** the electrodes. Assume all solutions are the same concentration (0.1M).

Figure 2. Screen shot of the click and drag tool.[28]

Treatment 2: Cartoon Tutorial Study. In the second treatment phase of the study, the goal was to examine how students responded to cartoon tutorials featuring molecular visualizations. The tutorials provided a laboratory context for the visualizations by showing how acidic solutions responded to electrical conduction tests and the tutor asked students to think about how and why the results would occur. Atomic level representations were scaffolded from minimalistic still images to complex and detailed animations. For example, initially in the tutorials the solute species were shown without water molecules to focus students on whether the species existed as mostly dissociated ions or remained intact, then hydration spheres were added to provide a sense for how water molecules attract to ions. Finally, the most detailed view was portrayed in the animations showing bulk water and the movement of the solute and solvent species. In total, the students viewed four cartoon tutorials, entitled:

1. *How a Conductivity Tester Works* (56 s). In this tutorial, Dr. Ann Ion teaches students how a conductivity tester works when testing aqueous solutions containing electrolytes.[31]
2. *Electrolytic Behavior of Acids—Strength of HCl* (2:03 min). In this tutorial, Dr. Ann Ion explains what constitutes a strong acid and shares how hydrochloric acid responds when tested for conductivity. Animations show the aqueous nature of the solution and how it responds when tested for conductivity.[32]
3. *Observing the Conductivity of Acetic Acid—Strength of Vinegar* (1:53 min). In this tutorial (Figures 3–5),

Figure 3. A still image of Dr. Ann Ion asking the viewer to consider how two acid solutions will conduct.

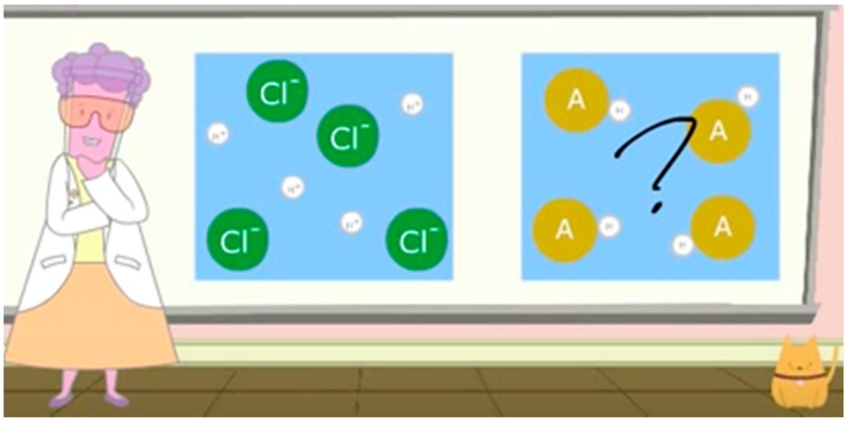


Figure 4. A still image asking students to consider how the species of acetic acid would dissociate compared to hydrochloric acid in light of the macroscopic evidence.

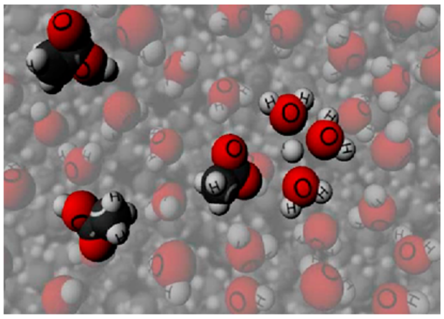


Figure 5. A still image from an animation portraying the atomic level nature of aqueous acetic acid, immediately after one molecule dissociated, to show the highest level of complexity portrayed in the tutorials.

Dr. Ann Ion shows a video of the macroscopic event in which acetic acid was tested for conductivity. She compares the solution to hydrochloric acid and discusses how to logically consider why acetic acid does not conduct as well as the strong acid, HCl.[33]

4. *Symbolic Representations of Strong and Weak Electrolytes and Nonelectrolytes—Chemical Equations* (3:27 min). In this tutorial, Dr. Ann Ion explains how to represent strong and weak acids through symbolic equations.[34]

After each tutorial, a metacognitive monitoring exercise was conducted as part of a semistructured interview in which each student was asked: (i) What new things did you learn from viewing the tutorial? (ii) What did you see in the tutorial that you already knew? (iii) Was anything confusing? This is an important exercise not only for revealing how students recognize variance, but also because it allows students to discuss mechanistic actions that they saw as being different, but had difficulty representing in their drawings. In this paper, students' responses were compared primarily to the information represented in videos 2 and 3 as these tutorials focused specifically on how a strong acid and a weak acid conduct electricity from both macroscopic and atomic level perspectives.

Revision of Initial Drawings. At the end of the study session, after students viewed all four videos and discussed their understanding of them, they were given the opportunity to revise their initial pictures of aqueous hydrochloric acid and acetic acid. They also orally described the changes they made in their revisions to convey their mental model of the chemistry events to help the researchers understand the meaning of the students' hand drawn, mental model depictions.

■ RESULTS AND DISCUSSION

Prior Knowledge of HCl(aq) and $CH_3COOH(aq)$

As part of the prior knowledge activities, students were first asked to predict whether acetic acid and hydrochloric acid, represented by the formulas HCl(aq) and $CH_3COOH(aq)$, would conduct when tested for electrical conduction (Table 1). Most of the students (17 of 24) correctly predicted that HCl(aq) would test strongly; however, only three students correctly predicted that acetic acid would conduct weakly.

Table 1. Analysis of Students' Prior Knowledge in Predicting the Conductivity Outcome of Aqueous Hydrochloric Acid and Acetic Acid and Examples of Their Justification

	Number Indicating Responses and Justification, $n = 24$	
Questions	Student Responses	Examples that Capture Students' Justification
Will HCl(aq) conduct?	No, not at all = 4	Recall = 2
		Guessed/Unsure = 1
	Weakly = 3	I learned which ones were strong acids = 2
		Number of atoms in the formula = 1
	Yes, strongly = 17	I had to memorize it = 11
		Dissociates in water = 3
		Guessed/Unsure = 3
Will CH_3COOH(aq) conduct?	No, not at all = 10	Guessed/Unsure = 6
		It is a base = 6
	Weakly = 9	It is not one of the strong acids = 3
		It is a base = 5
		Guessed/Unsure = 7
	Yes, strongly = 5	It is made of lots of atoms = 3
		Guessed/Unsure =3

Many students (10 of 24) predicted that acetic acid would not conduct at all, while five students thought it would conduct very strongly (Table 1). Students were interviewed to examine how they justified their prediction. Their responses were coded and organized by trends in their oral responses. In general, reasons students gave to justify their prediction typically did not address the particulate nature of matter and focused more on recognizing that it was a memorized fact. For example, 11 students stated that they knew HCl was a strong acid because they had to memorize it for class. Only three students recognized that it dissociated into ions as an explanation for why it conducts. In regard to acetic acid, 16 students confessed to guessing on their prediction. This was rather large in comparison to predictions for HCl's conduction ability, in which only four students were unsure. In general, students successfully predicted the conductivity of aqueous hydrochloric acid, but were less successful predicting the conductivity of aqueous acetic acid. For both acids, students' justifications lacked detailed explanatory connection to the submicroscopic level and many confessed to guessing or to recollection of facts they had committed to memory.

Since very few students disclosed their understanding of the submicroscopic level in their justification for predicting conductivity test outcomes, it was vitally important that the students be tasked with constructing submicroscopic level pictures of the events as this would help us later discern how they viewed their understanding as varying from the tutorials. Thus, in the second activity, students were specifically asked to construct pictures with click and drag tools to represent their mental model of both aqueous hydrochloric acid and aqueous acetic acid, of the same concentrations (0.1 M), as the solutions were tested for electrical conduction. Students were then asked to orally describe their pictures to further explain the meaning behind what they constructed and their mechanistic understanding.

Students' pictures and oral explanations of aqueous hydrochloric acid and acetic acid were coded against a list of key events depicted in the tutorials to track features that students had in common with the tutorials, as well as features that varied from the tutorials. The tutorials were designed to scaffold complexity from the most simplistic solute species to the meticulous detail of the hydration sphere and solvent water to be consistent with the range of details noted by experts, in previous research, who were asked to describe the key attributes of these aqueous acidic solutions that they would expect their best general chemistry students to be able to describe.[35] While the second tutorial explicitly showed how the strong acid, hydrochloric acid, conducted, the third tutorial did not explicitly show how aqueous acetic acid would respond to a conductivity tester. Thus, students were required to apply how the species of a weak acid would behave based on their understanding of the strong acid's response and also their understanding of the structural nature of the weak acid, which was explicitly described as being comprised of mostly molecules and only a few dissociated ions. The pictures were coded using the constant comparison method, in which the pictures and oral descriptions that students made were compared to the main structural features of both aqueous hydrochloric acid and aqueous acetic acid that were explicitly conveyed in the tutorials.[36,37] In addition, how the students constructed their understanding of the conductivity mechanism involving the movement of ions toward their respective electrodes was examined. The codes were validated through inter-rater reliability.[36,37] A colleague examined the raw data and coded them according to short descriptions made by the first author noting the key structural features depicted in the tutorials, specifically the nature of the ion species, the hydration of the ions with immediate hydration spheres, and how the ions would move during conduction. The researchers then discussed any discrepancies between their codes and came to consensus (99% agreement).

Mental Models of Aqueous Hydrochloric Acid Tested for Electrical Conduction

Before Treatment. Prior to viewing the videos or observing any atomic level animations related to electrical conductivity, students' pictures, representing their mental models of the event, seemed strongly influenced by the symbolic or formula representation of hydrochloric acid so often observed in equations. Roughly half of the students represented molecules of HCl in their pictures (Figure 6) with little or no water molecules represented and no obvious connection between ion presence and mobility as connected to conductivity. Some students (11 of 24) conveyed that the strong acid was completely dissociated into ions indicating that they had a mental model of the structural makeup of the solution, but few represented an understanding of conductivity being attributed to mobile ions

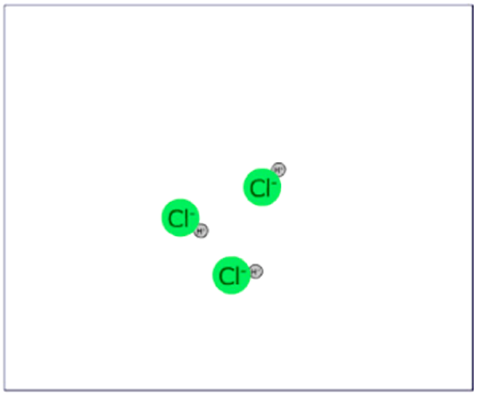


Figure 6. An example of an aqueous hydrochloric acid solution made by student Mg before viewing the video tutorials.

attracted to their respective charged electrode. Not one student authentically represented bulk water as comprised of a network of water molecules in close proximity to each other, and only five students represented water molecules as attracted to the ionic species in solution; however, this was not surprising as previous studies indicate that this is a typical shortcut that students make.[1,5,6]

After Treatment. At the end of the study, when the students were allowed to revise their pictures to reflect their enhanced mental model, nearly all of the students represented the strong acid solution as composed of completely dissociated ions with only two students persistently maintaining that some molecules must exist in solution (Table 2). In addition, most students (19 of 24) revised their pictures and consequently their mental models to show the ions attracted to their respective electrodes indicating that they learned that electrical conduction is caused by ions changing position to move to their respective electrodes (Figure 7). Students also orally recognized the importance of representing water molecules and sometimes discussed its presence, but most did not represent a realistic sense of bulk water as this would be "hard to draw" and many felt it was not as important as depicting the ions and their movement. In this case, students' pictures were not consistent with their mental model of the event.

Table 2. Analysis of the Key Features and Misconceptions Students Described in Their Pictures and Oral Descriptions of Atomic Level Aqueous Hydrochloric Acid Tested for Electrical Conductivity before and after Video Treatments

Features and Misconceptions Students Described	Number Indicating a Feature or Misconception, n = 24	
	Pretreatment	Posttreatment
Key Features of Dilute Hydrochloric Acid Solution Is Tested for Conductivity		
Completely dissociated into ions	11	22
Hydration spheres/ion-dipole intermolecular forces	5	13
Bulk water as a network (close proximity)	0	2
H^+ ions attract to the negative electrode	7	19
Cl^- ions attract to the positive electrode	6	19
Misconceptions Students Constructed/Described about a Dilute Hcl Solution Tested for Conductivity		
Ion pairs or molecules (no charges)	13	3
Unorthodox placement of species (middle, near wrong electrode)	15	6
No water molecules represented	6	3
Ions do not attract to electrodes	12	4
Ions attract to the wrong electrodes or molecules attract to the electrode	3	2

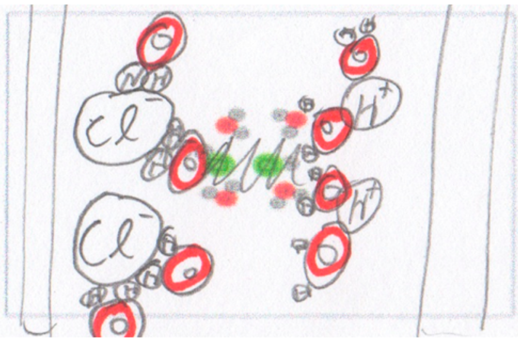


Figure 7. An example of Student Al's revised picture of aqueous hydrochloric acid tested for electrical conductivity.

Mental Models of Aqueous Acetic Acid Tested for Electrical Conduction

Before Treatment. Aqueous acetic acid was a challenging solution for students to represent prior to experiencing the tutorial treatment, and there was considerable range in how students constructed their pictures prior to viewing the tutorials reflecting that students' mental models were not well formed as students admitted to guessing. The majority (14 of 24 students) represented it as composed of molecules of CH_3COOH (Table 3); however, several students (9 of 24) depicted acetic acid as a strong acid with hydrogen ions prominently represented in their pictures (Figure 8). This was likely because students noticed that the relatively large molecule had many hydrogens and must break apart to produce hydrogen ions, a characteristic of acidic

Table 3. Analysis of the Key Features and Misconceptions Students Describe in Their Pictures and Oral Descriptions of Atomic Level Aqueous Acetic Acid Tested for Electrical Conductivity

Features and Misconceptions Students Described	Number Indicating a Feature or Misconception, n = 24	
	Pretreatment	Posttreatment
Key Features Students Construct/Report When Dilute Acetic Acid Is Tested for Conductivity		
Molecules of CH_3COOH present	14	20
Ratio of H^+ to CH_3COO^- = 1:1	4	18
Acetic acid molecules are dominant solute species; Number of solute ions less than number of solute molecules	5	16
Bulk water as a network of many water molecules	0	1
H^+ attracts to the negative electrode	3	7
CH_3COO^- attracts to the positive electrode	5	5
CH_3COOH does not attract to the electrodes	15	19
Misconceptions Students Constructed/Reported about Dilute Acetic Acid Tested for Conductivity		
Only acetic acid molecules, no ions represented	7	0
Strong acid represented. H^+ ions are prominent	10	6
Improper ion formation or # of acetate ions does not equal H^+ ions	10	6
No conductivity mechanism represented	16	15
Like charges attract or ions near incorrect electrode	1	2

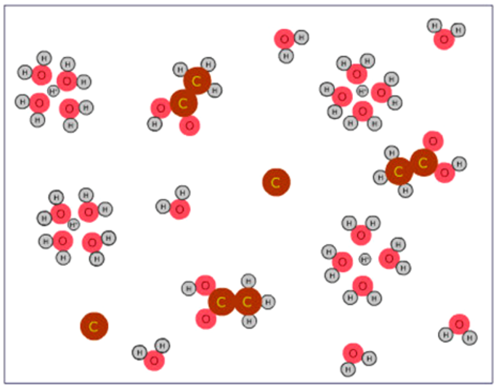


Figure 8. An example of Student Ne's representation of aqueous acetic acid before viewing tutorials in which one acetic acid molecule dissociates into separate atoms.

solutions. Only four students depicted a one-to-one ratio of hydrogen ions to acetate ions; however, none of these students represented the acetic acid molecule as the dominant species. Most of the students (15 of 24) did not represent the molecules of acetic acid as attracted to the electrodes (Table 3), which may reflect that students did not have a well formed mental model of electrical conduction in spite of viewing a tutorial that addressed how a conductivity tester worked. Only five students acknowledged the presence of water molecules through hydration spheres or ion-dipole attractive forces, but none represented bulk water as a network of many water molecules.

After Treatment. At the end of the study, when the participants were given the opportunity to revise their initial pictures to reflect their enhanced mental models, all of the students made changes to their pictures indicating that they recognized that their understanding varied from the tutorials. The largest gains were made in structural representation of the acetic acid solution (Figure 9). Most students (16 of 24) recognized that the solution was composed of primarily acetic acid molecules and many students (18 of 24) demonstrated that for every hydrogen ion or hydronium produced there was an equal number of acetate ions in solution (Table 3). Most students continued to omit water molecules from their bulk water representations stating that it would complicate things too much to include them. There was little gain in participants' ability to describe the mechanism of electrical conduction for this weak acid even though the electronic click and drag tool specifically required that they consider how the solution would look as it was tested for conductivity. Many students failed to recognize that the acetate and hydrogen ions would be attracted to their respective electrodes. The nature of how aqueous acetic acid conducts was never explicitly shown to the students, but it was still surprising to see that only 7 of the 24 students represented hydrogen ions as attracting to the negative electrode and 5 of 24 students represented acetate ions attracting to the positive electrode (Table 3). This may indicate that students' mental models of electrical conductance are still uncertain or it could mean that students were so preoccupied with correcting the structural features to match with the pictures depicted in the tutorial representations that they overlooked how the ions would respond in the presence of an electric field.

Metacognitive Monitoring: What New Things Did You Learn?

After each "Strength of HCl" and "Strength of Vinegar" tutorial was viewed, students were presented with a metacognitive monitoring task and asked: What new things were learned from viewing the tutorials? This question was specifically focused on learning how students perceived variations between their mental models and the tutorial representations. To examine when students recognized commonalities or a lack of variance between the tutorials and their mental models, the students were asked: What did you already know or what features matched your understanding? The raw data from the metacognitive monitoring tasks were consolidated and phrases that represented typical student responses were identified and then used to recode all of the student responses as they fit under these phrases.[36,37] The phrases (Table 4) were then shared with a colleague who independently coded students' descriptions as they fit with the phrases.[36,37] The codes were discussed and consensus (98% agreement) was reached. The phrases were further organized as they fit under three categories: (1) Structure—Particulate Nature of the Solution, (2) Function—Conductivity Mechanism, and (3) Evidence and Facts—features that were emphasized in the tutorials (Table 4). In addition, students were also asked to rate themselves on how familiar they were with the concepts presented in the two tutorials and whether, in their opinion, it had taught them anything new (Table 5).

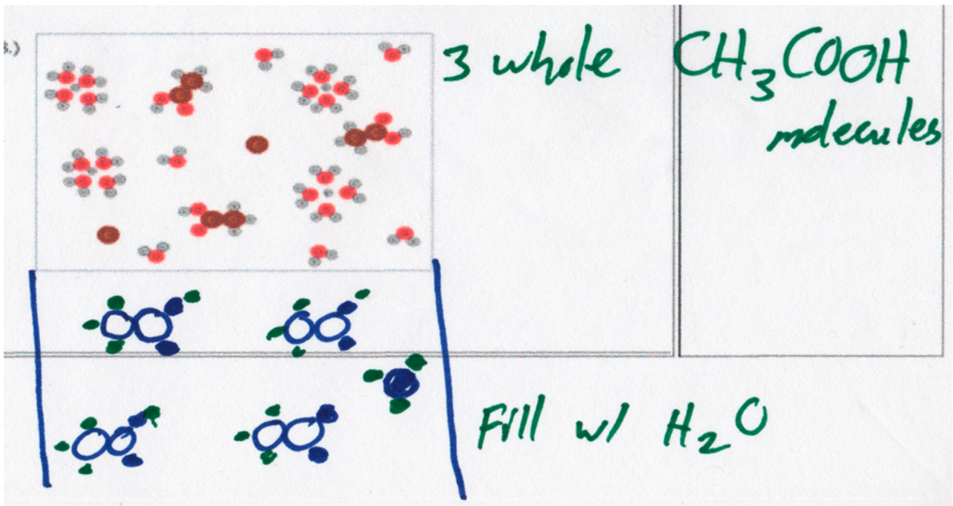


Figure 9. An example of Student Ne's revised representation of aqueous acetic acid after viewing the tutorials.

Table 4. Student-Identified Features from the Videos That Were New to Them and with Which They Were Already Familiar

Features by the Three Categories	Number Indicating Newness or Familiarity, $n = 24$ New	Familiar
Tutorial: Strength of HCl		
1. Structure—Particulate Nature of the Solution		
HCl breaks apart/is dissociated/is separated into ions	14	5
Ions were surrounded by water—solvated ions, hydration spheres	8	0
2. Function—Conductivity Mechanism		
Movement of ions/species to electrodes	9	2
3. Evidence and Facts		
HCl conducts strongly (Evidence)	8	4
HCl is a strong acid (Fact)	9	4
Tutorial: Strength of Vinegar		
1. Structure—Particulate Nature of the Solution		
Concentration: [Only a few dissociate], [one out of four dissociate], or [the solution contains mostly molecules]	17	1
2. Function—Conductivity Mechanism		
Movement of ions/species to electrodes	6	0
3. Evidence and Facts		
[It] conducts weakly (Evidence)	4	3
Acetic acid is a weak acid (Fact)	11	4

Table 5. Self-Ratings of Learning Experience with Tutorials

Self Ratings	Number Indicating Rating for the Tutorials, $n = 24$ Tutorial 2: *Strength of HCl*	Tutorial 3: *Strength of Vinegar*
"[It] was all new or quite a bit was new."	4	15
"I knew some things, but I learned a lot too."	12	5
"A little bit was new or I knew all of [it]."	8	4

Structure—Particulate Nature of the Solution. During the metacognitive monitoring activity, in which students were asked to describe how the tutorials were similar to or different from their initial understanding, students expressed having the greatest gain in understanding of the particulate nature of both hydrochloric acid and acetic acid after viewing the tutorials. This was uncovered by the many phrases in which students described the species that made up the solutions as being new to them and at variance to their initial understanding. This finding is also consistent with their picture revisions in which students showed considerable improvement in their understanding of the solutions after their experience with the tutorials. The result also makes sense, because the tutorials vividly showed atomic level details of the solutions with still images of the key solution species emphasized. These focal points likely assisted students with recognizing how their understanding varied by comparison.

Function—Conductivity Mechanism. The mechanism of conductivity whereby an aqueous acidic solution conducted because of the presence of mobile ions in an electric field was articulated as a novel event by less than half of the students; however, only a few students reported that HCl's conductivity was familiar to them, and none reported that acetic acid's conductivity was familiar to them. It is important to recognize that, while students did not express that the conductivity mechanism was new to them, most (19 of 24) revised their drawings to represent the mechanism with HCl, illustrating hydrogen and chloride ion migration toward the electrodes. One reason students may not have orally recognized the novelty of the mechanism was that they believed that they accurately predicted that the acids would conduct, thus confusing familiarity of the prediction with understanding the nature of the mechanism. It is also possible that students had limited understanding of what causes conductivity (the mechanism), and as a result they did not possess the cognitive ability to fully understand what was shown to them in the tutorials.[16] Even after students viewed the tutorial on how a conductivity tester works, it may have been challenging for students to apply what they learned from this tutorial to the other tutorials. If they did not actually understand the conductivity mechanism, then this would support the hypothesis that they replicated what they saw or heard in the tutorials, recognizing that features were at variance with their depiction, but they still may not understand the cause of the ion mobility toward the electrodes. In the case of acetic acid, even fewer students (6 of 24) recognized the conductivity mechanism as something that they learned from the videos. However, in the videos, it is important to again remember that the conductivity mechanism of acetic acid was never explicitly shown. It seems that students were unable to apply their understanding of how the dissociated ions of hydrochloric acid conduct to account for how acetic acid ions might also behave.

Evidence and Facts. The videos were a strong effort to help students relate how macroscopic evidence informs our understanding of the atomic level. For example, the students were shown that a solution that strongly conducts has many ions present and a solution that does not conduct as well would have fewer ions present. Concentration and dissociation were discussed, and the cartoon tutor recommended testing two acids of equal concentration before considering why they might conduct differently. Most students were unaware of the explicit connection between macroscopic and atomic levels. They tended to reference these levels separately. In general, students seemed to accept what the tutorials told them as they tried to match their pictures to what they saw. Many students picked up on factoids that were included in the videos, such as learning that acetic acid is vinegar and that it was a weak acid, while HCl was described as a strong acid. This connection to facts may stem from students' class experience, and it is consistent with how students responded in the prior knowledge worksheet exercise.

Self-Ratings. Analysis of students' self-ratings indicates that students felt they learned most from the tutorial on "Strength of Acetic Acid". Some students commented that they were not as familiar with acetic acid, even though all of the students have used this common household acid in the laboratory associated with the course. Many found the formula daunting when they were asked to first construct their pictures, and as previously mentioned, some thought it was actually a base due to the $-OH$ in the formula CH_3COOH. Many were surprised to learn that acetic acid was vinegar. While students felt they had the largest learning gain from the tutorial on acetic acid, most were unable to deduce how it would conduct. Students felt that, even though the video on "Strength of Hydrochloric Acid" was a review, they learned a great deal and this was supported by the improvements made in their picture revisions and in their metacognitive activity.

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CONCLUSIONS

This study was designed using the theoretical framework, variation theory, which guided the researchers' conceptualization of the study to examine two constructs (mental models and metacognition) for unpacking how students recognized variance between their understanding of structural and mechanistic features of acid solutions tested for electrical conduction and the portrayal represented in cartoon tutorials. Data analysis focused on identifying the nature of the variance. This study is the first to explore how tutorials that scaffold animations with an instructional classroom-like cartoon context affect students' ability to learn.

What Kinds of Information Portrayed in Cartoon Tutorials Do Students Identify as New or Familiar to Their Mental Models?

In general, molecular visualizations taught through a cartoon tutorial caused students to notice variance between their initial mental models and the critical features portrayed in the tutorials during the metacognitive monitoring activity more often than they reported noticing aspects that were familiar to them. Most students recognized the novel aspects of the solution species, and they discussed the particulate nature of the acid solutions. Specifically, many students learned something new about the dissociated species and hydration of these ions. These were structural features that were emphasized by the cartoon tutor prior to introducing the visualization. Fewer students reported that the conductivity mechanism was new to them, but this did not imply that they found it familiar as only 2 of 24 students recognized the mechanism as something they already knew. According to Bussey et al., experiencing variation in a particular feature, such as the particulate nature of solutions, may help students notice that feature, while other features, such as mechanisms, may fade into the background.[26]

How Do They Express Modification to Their Mental Models through Pictorial Construction and Oral Descriptions?

The students recognized variation between the information portrayed in the tutorials and their initial mental models as conveyed through their picture revisions. The tutorials influenced students to incorporate more key features in their pictures and less misconceptions. While students improved most drastically in their portrayal of the conductivity mechanism of aqueous hydrochloric acid that was explicitly depicted with 19 of 24 students showing ions attracting to the appropriate electrode, only 6 of 24 students described the conductivity mechanism involving aqueous acetic acid, which was not explicitly depicted. The difficulty students have applying a newly learned concept is not surprising, and it is consistent with a previous study in which it was reported that transferring understanding about aqueous salt dissolution to describe the same salt solution involved in a precipitation reaction was challenging for students.[6] In this study, when students were presented with visualizations in the tutorial context, certain features were emphasized by the cartoon tutor, which likely compelled students to recognize the variance and trust that the images in the tutorial were a better representation than their existing mental model. Most, if not all, students made an effort to adjust their pictures to be more consistent with the tutorials. The range of the improvements varied and was likely dependent on students' cognitive ability to recognize the variation and understand why it was in variance, which is consistent with previous theories on learning from visualizations.[16] However, when the information is not explicitly modeled, students may be reluctant to apply what they learned, because they may not feel that they completely understand it, and they fear being wrong. Thus, they only represent the information that was validated by the tutorial and explicitly modeled to perhaps lower their risk of being incorrect. This may be a problematic attribute of visualizations presented via tutorial.

Implications for Instruction

In conclusion, our findings indicate that, when students viewed molecular visualizations in the scaffolded context of a tutorial, they recognized variation between their mental models and the tutorial models quite well. It may comfort instructors to know that if they assign students to view a video or visualization for home study, similar in design to these videos, their students will likely notice and recall explicit structural and mechanistic differences. However, even though they recognize that their understanding has aspects both in common and different from what they saw, they may not fully understand why or how these atomic level representations and mechanisms account for macroscopic evidence. Thus, it is crucial that instructors consider how students should practice making these connections in their classes and laboratories and they should not assume that students deeply understand what they have viewed or have the ability to relate structure to function on their own. Activities, like the ones used in this study, in which students draw their understanding and think about how it compares and contrasts to what they see in the tutorials are recommended pedagogical tools that instructors should consider implementing in their teaching practice as they will lend insight into what students think.

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Notes

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