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Multimedia and Understanding: Expert and Novice Responses to Different Representations of Chemical Phenomena

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Abstract: In two experiments, we examined how professional chemists (i.e., experts) and undergraduate chemistry students (i.e., novices) respond to a variety of chemistry representations (video segments, graphs, animations, and equations). In the first experiment, we provided subjects with a range of representations and asked them to group them together in any way that made sense to them. Both experts and novices created chemically meaningful groupings. Novices formed smaller groupings and more often used same-media representations. Experts used representations in multiple media to form larger groups. The reasons experts gave for their groupings were judged to be conceptual, while those of novices were judged to be based on surface features. In the second experiment, subjects were asked to transform a range of representations into specified alternative representations (e.g., given an equation and asked to draw a graph). Experts were better than novices in providing equivalent representations, particularly verbal descriptions for any given representation. We discuss the role that surface features of representations play in the understanding of chemistry, and we emphasize the importance of developing representational competence in chemistry students. We draw implications for the role that multiple representations—particularly linguistic ones—should play in chemistry curriculum, instruction, and assessment. © 1997 John Wiley & Sons, Inc. J Res Sci Teach **34:** 949–968, 1997.

The expansion of the universe, tectonic plate drift, evolution of the species, and molecular structure and reactivity are all scientific phenomena that are not available to direct experience. Whether the phenomenon is cosmological, geological, biological, or chemical, our window on the world is really very small. But perhaps more than other sciences, understanding chemistry relies on making sense of the invisible and untouchable. Much of what is chemistry exists at a molecular level and is not accessible to direct perception. Whereas the experiments used in classroom demonstrations are carefully selected to denote chemical processes by changing color, precipitating a solid, or giving off heat, most chemical reactions in the real world occur at rates that are so fast or slow, or their products are so dispersed, colorless, or odorless, as to make them difficult to detect.

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Consequently, chemistry as a field of study is inherently representational or symbolic. Chemists have invented specialized symbol systems—such as reaction equations, molecular structure diagrams, concentration graphs, and three-dimensional (3D) computer models—to represent the molecular phenomena that they study in their laboratories (Crosland, 1962; Hoffmann & Laszlo, 1991), and they use these to communicate their understanding to their peers (Kozma, Chin, Russell, & Marx, 1997). Chemists also use these representations to communicate their understanding to students. Classroom whiteboards and modern chemistry textbooks are filled with diagrams, charts, graphs, equations, and formulas along with words, photographs, and illustrations. Increasingly, newer educational technologies—video and computers—are also being used in the classroom to represent chemical phenomena in new ways (Illman, 1994). But do chemistry students understand these representations to mean what chemists intend? Do they have the necessary prior knowledge to begin to see the principles in the images?

This laboratory study examined similarities and differences between experts and novices in chemistry on two multimedia cognitive tasks. The study complements our ethnographic research, which looks at chemists as they use different representations to solve problems in their research laboratories (Kozma et al., 1997). The goal of this program of research is to describe the role that various representations play in the thinking and work of chemists and to draw implications for chemical education and the design of multimedia environments for students. More specifically, we are interested in how environments that employ multiple linked representations might best be designed and used to support and assess student learning in science (Kozma, Russell, Jones, Marx, & Davis, 1996; Russell & Kozma, 1994).

We define multimedia not in terms of particular hardware configurations but as different symbol systems that can be used to represent information in different ways (Kozma, 1991). It is postulated that symbol systems vary in their surface features and that the surface features of one symbol system or symbolic expression may better represent certain characteristics of information relative to another symbol system, at least for certain learners and tasks. The prospect is that multiple symbol systems, or multimedia, may work together to provide useful external representations for novices that experts are able to provide for themselves. As a result of using multimedia, novices may come to understand the domain in more expert-like ways. This possibility implies a need for a deeper understanding of how both experts and novices use different media.

Research on expertise distinguishes experts from novices primarily by the ways they organize their knowledge in a domain and use this knowledge to solve problems and understand the world around them (Glaser, 1989; Glaser & Chi, 1988). The knowledge of experts consists of a large number of interconnected elements that are stored and recalled as extended, coherent chunks of information organized around underlying principles in the domain. Experts use the structure of this knowledge to perceive and recognize underlying patterns and principles in problem situations; they virtually "see" a problem different from the one novices do. For example in response to a typical textbook physics problem (Chi, Feltovich, & Glaser, 1981; Larkin, 1983; Larkin, McDermott, Simon, & Simon, 1980), expert physicists evoke underlying principles such as force or energy. They use these principles to build a mental representation, or mental model, of the situation that includes mental entities corresponding to both the physical objects encountered in the problem (such as blocks, springs, pulleys, etc.), as well as formal constructs (such as force vectors, friction, and velocity) that have no direct, concrete referent in the real world. Experts use this mental model to test and select potential problem solutions.

In contrast, the knowledge of novices is sometimes characterized as unconnected fragments that correspond to common experiences with the everyday world, experiences such as pushing, throwing, and overcoming an opposing force. diSessa (1988, 1993) characterized the knowledge of novices as composed of many small knowledge structures that he calls "phenomenological primitives," or "p-prims." These structures are phenomenological in that they are based on superficial interpretations of experienced reality. They are primitive in that they are self-explanatory—something happens because that's the way things are. In physics, for example, identified p-prims include notions of force, resistance, and equilibrium, among other structures. However, these notions are not the formal principles of physicists that go by these names but the intuitive experiential realities of force as mover, resistance as pushing back, and equilibrium as two forces that cancel each other out. While these p-prims are typically unconnected and unsystematic in the minds of novices, they provide an important knowledge base on which formal concepts and principles are built. Gradually, p-prims cluster and become organized into more complex, formal knowledge structures. As expertise develops, these p-prims continue to be used as intuitive examples of formal theory. Consequently, diSessa and others (Smith, diSessa, & Roschelle, 1993) see expertise as developing in a more or less direct and continuous way from the earlier experiences of notices.

However, these phenomenological primitives have their limitations. When confronted by textbook physics problems, novices will construct a mental representation using surface features of the situation, as do experts (Chi et al., 1981; Larkin, 1983; Larkin et al., 1980), but their internal representations are composed primarily or exclusively of the familiar, visible objects and experiences (i.e., p-prims) referenced in the problem. Their mental representations tend not to contain entities that correspond to the underlying principles of physics, or this information is inaccurate or incomplete. Novices operate on these mental entities in ways that correspond to operations in the real world (e.g., mentally push on blocks and pull on springs), but because these mental structures lack representations of formal principles, they are insufficient to determine a solution. Whereas experts use their prior knowledge to see underlying principles in a problem situation, novices see only primitive objects and events.

The studies of expertise described above (Chi et al., 1981; Larkin, 1983; Larkin et al., 1980) used text to represent the objects and events in the problems they presented to their subjects; they did not use pictures, diagrams, and other representations. However, the implication is that experts can use their prior knowledge to see through the surface features of various representations to construct their own principle-based understanding of the problem, regardless of the symbol system or medium used. Without this prior knowledge, the understanding of novices is both enabled and constrained by the surface features of the representation that is used and the phenomenological primitives that it evokes. That is, whereas experts may understand a concept expressed in several forms to be the same or may be able to transform a concept expressed in one form to another, the understanding of novices may be strongly influenced by the elements, forms, shapes, objects, and events embedded in a particular symbolic expression. They may have a very different understanding of the same phenomenon if expressed in one symbolic form or another, and they may not be able to make transformations across different forms. These are the hypotheses we explicitly tested in this study.

It is a well-documented fact that students come to chemistry with significant deficiencies in their understanding of chemical principles and their ability to represent these symbolically (Nakhleh, 1992; Bodner, 1991; Herron, 1990; Krajcik, 1991). A study by Kozma, Russell, Johnston, and Dershimer (1990) illustrates this point. These researchers used a variety of open-ended questions about chemical equilibrium to compare the understanding of undergraduates taking general chemistry (novices) with that of advanced doctoral students in chemistry (experts). On the basis of responses to these questions and think-aloud protocol analysis, the researchers found that experts displayed an understanding of chemical equilibrium organized around thermodynamic principles and concepts such as free energy, enthalpy, and entropy, but the understanding of novices was incomplete and fragmented and exhibited a number of significant misconceptions. For example, a number of undergraduates believed that although a system at equilibrium became dynamic when it was perturbed in some way (e.g., a reagent was added, the temperature was increased), the reaction came to a stop when the system reached equilibrium.

Students also have difficulty in understanding various symbol systems and symbolic expressions as representing real-world phenomena or scientific principles and processes. A study by Yarroch (1985) examined verbal protocols of high school chemistry students and found that although all of the students could successfully balance chemical equations, most could not draw diagrams that were reasonably consistent with the equations. Students confused chemical coefficients and subscripts, so that they would typically represent three hydrogen molecules ($3H_2$) as six linked circles. While many chemistry students appear to master the symbolic skills of chemistry, they often do so by treating equations as mathematical puzzles in which the numbers on the two sides of the equation have to equal each other, rather than thinking of the equation as a representation of a dynamic and interactive chemical process (Krajcik, 1991).

Given these difficulties, one must wonder what students understand when they see an experiment, an equation, a graph, or an animation of chemical phenomena. When different chemical symbol systems are used to represent the same phenomenon, do students understand them to correspond to the same system or do they understand something different from each? How does this understanding differ from an expert's?

The research reported in this study examines how experts and novices in the domain of chemistry respond to different representations of a set of situations and experiments related to chemical equilibrium. We compare experts and novices in their sorting of several chemical systems and experiments, as represented in various ways. We also examine how experts and novices differ in their ability to make transformations across different representational forms. This research extends our earlier work on expertise in chemical equilibrium (Kozma et al., 1990) to explicitly examine the relationship between understanding and representational form. It also informs efforts to develop software that uses multiple linked representations to help students understand chemistry (Russell & Kozma, 1994; Kozma et al., 1996; Russell, Kozma, Jones, Wykoff, Marx, & Davis, 1997). Knowledge of how novices and experts differ in their understanding of various representational forms might provide multimedia design principles that use surface features to help students develop deep knowledge structures and facilitate the transition from novice to expert-like performance.

Experiment 1: Sorting Task

Method

Subjects. The same subjects were used in both experiments. The novices were 10 undergraduates from a midwestern university. Five were 18 years old and 5 were 19 years old. Five were males and five were females. All were enrolled in a first-semester chemistry course, and all had taken chemistry in high school. Eight were majoring in engineering and two in health science. There were 11 experts; 5 were professional chemists working at a pharmaceutical laboratory, 5 were doctoral students in chemistry, and 1 was a community college chemistry faculty member.

Experimental Task. Differences between experts and novices are frequently measured by giving members of each group a cognitive task or problem and asking them to think aloud while they solve it (Ericsson & Simon, 1993). This approach makes explicit the knowledge that subjects have stored in memory related to the task domain, how they structure this knowledge, and

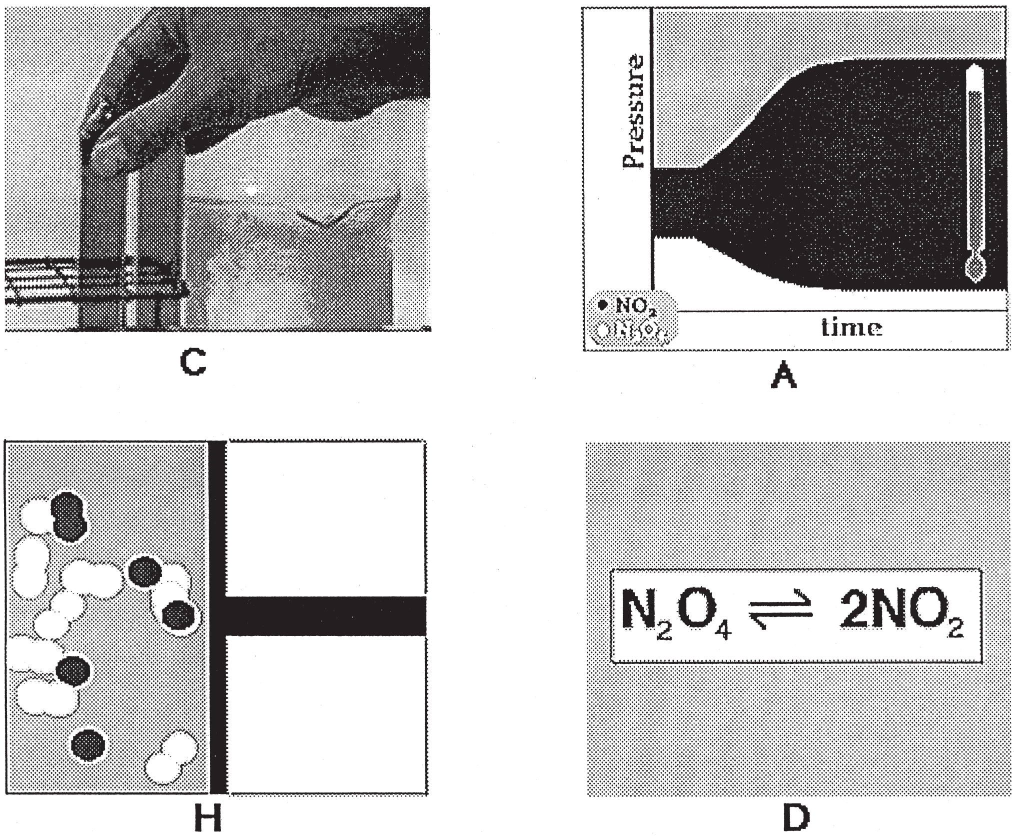

Figure 1. Examples of cards and their labels for each of the four types of media taken from computer displays and used in the sorting task: videos (C), graphs (A), animations (H), and equations (D). Originals were in color.

the mental procedures they use to operate on this knowledge to solve the problem. These think-aloud protocols are analyzed to highlight differences between experts and novices in their knowledge and problem-solving skills. However, this approach is not recommended to assess differences between experts and novices in skills that require extensive visual encoding and processing, because it is felt that think-aloud methods do not make this knowledge and skill explicit (Ericsson & Simon, 1993). Since visual encoding and processing of various representations is at the core of the current study, we chose indirect methods for assessing expertise (Olson & Biolsi, 1991). Two tasks were constructed for this study that involve indirect measures: One task asked subjects to sort various representations into meaningful groupings (Experiment 1), and the other asked them to transform representations from one form to another (Experiment 2).

For the sorting task, subjects were given a deck of 14 cards, each corresponding to a computer display, as described below. Each 4 × 6-inch card showed a still frame from a computer display, in color, with a letter on the front, from A through N. The displays differed in the type of medium or symbol system used to represent the chemistry: graphs, animations, video segments, and equations. Several examples of the cards are shown in Figure 1. Figure 2A shows how these cards were distributed across media. This constitutes one theoretical structure that subjects might use to organize their sort, a *media* theoretical structure. That is, subjects could

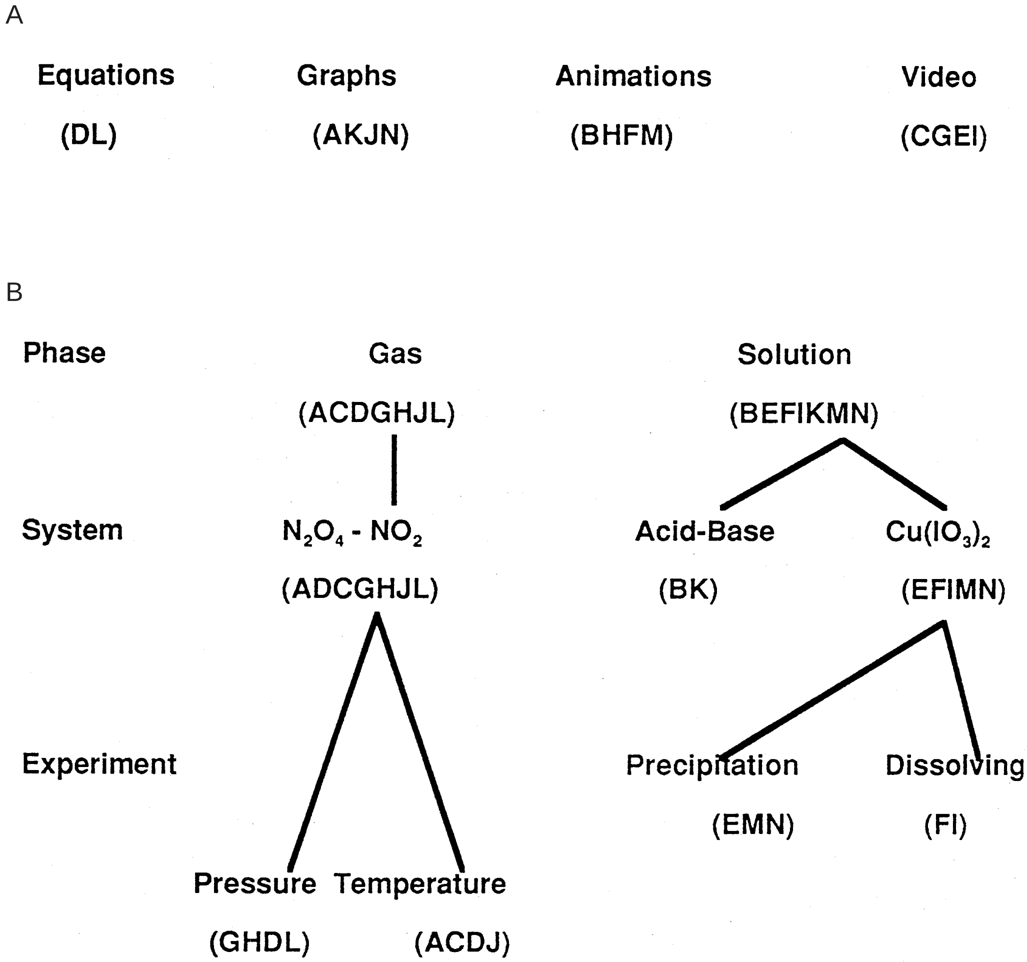

Figure 2. Alternative theoretical structures that could be used for sorting by media (A) or chemistry (B).

choose to sort their cards by media, in which case they could create the groupings shown in Figure 2A.

The cards also differed in chemical content, and the subjects could choose to sort their cards according to some chemical scheme. Figure 2B shows alternative theoretical structures of the chemical content that subjects might use to sort the cards: phase (gas or solution), chemical system [N_2O_4, acid-base, $Cu(IO_3)_2$], and experiment (pressure change, temperature change, precipitation, or dissolution).

As mentioned above, each card corresponded to a computer display. All of the displays except for equations were QuickTime movies 10–40 s in duration. Each display used the surface features of a particular symbol system (graphs, animations, video, or equations) to portray one of the above chemical reactions. For example, graph displays used moving lines or filled-in areas on a coordinate plane to show changes in partial pressure or concentrations of species (on the Y axis) developing over time (on the X axis). Animations used dots or circles joined in different-size clusters and of different colors moving across a 2D space to depict molecules of different species colliding, bouncing, and reacting over time. Video segments showed experiments as they are conducted on the lab bench and displayed objects and events typically found in chemistry laboratories. The static equation displays used standard chemical notations to show a reaction equation and the equation for an equilibrium constant.

Procedure. Subjects participated individually in one session lasting about 90 min, during which they engaged in two tasks: sorting and transformation. The sessions were audio- and videotaped.

During the administration of the sorting task, the experimenter operated the mouse to show a subject the computerized display that corresponded to each of the cards. After viewing all of the displays, the subject was asked to sort the corresponding cards into as many groups as he or she wanted, for whatever reasons wanted. The subject could make as many groups as desired, and a group could be a single card or as many as the subject wanted. The subject was told that the groups could include different numbers of cards or the same number. The computerized displays could be reviewed in any order and as often as desired. When the subject was finished with the sort, he or she was asked to try to name or describe each group or to give reasons for the sort.

When this first sort was completed, the subject was then given a new deck (identical to the first) and asked to sort the deck in another way. The procedure for this second sort was identical to that for the first.

Results

Size of Sorts. A common distinction between experts and novices is the size of chunks, or patterns they create from information and situations they encounter (Glaser, 1989). Experts perceive large, meaningful patterns; novices do not. In examining the size of sorts in the current study, the data support the finding of earlier studies. The average sizes of the groups created by experts were larger than those of novices. For the first sort, the mean number of cards in groups created by experts was 3.23, Standard derivation (*SD*) = 1.82, whereas the mean number of cards in groups created by novices was 2.15, *SD* = .89, $F(1, 19) = 17.26$, $p < .0001$. For the second sort, the mean size of groups created by experts was 3.35, *SD* = 1.61; for novices, it was 2.62, *SD* = 1.06, $F(1, 19) = 6.65$, $p < .01$. Across the two sorts, experts created groups with seven or eight members eight times. The largest group created by novices had five members, and this happened only five times across the two sorts.

Correspondingly, novices created significantly more groups than did experts. For the first sort, experts created a mean of only 4.4 groups, *SD* = 1.69, with the 14 cards, whereas novices created a mean of 6.5 groups, *SD* = .71, $F(1, 19) = 13.75$, $p = .0015$. In the second sort, experts created a mean of 4.18 groups, *SD* = 1.47; novices created a mean of 5.33 groups, *SD* = .86, $F(1, 19) = 4.28$, $p = .053$. Across the two sorts, 8 novices and 1 expert created six groups, and 6 novices and 3 experts created seven groups.

Composition of Sorts. To understand how experts and novices organize their knowledge and how this might interact with information expressed in different media, an analysis of the size of groupings must be complemented by an analysis of composition of the sorts: What do experts and novices group together? Do experts and novices group items differently? Do notices rely more on surface features of the medium while experts base their sorts on underlying chemical principles? Do experts and novices organize their groups differently between their first and second sorts?

We began our analysis by using the theoretical structures in Figures 2A and 2B. There were relatively few sorts that completely matched any of these theoretical structures, but all of the sorts that did match them were made by experts. On the first sort, 2 of the 11 experts made a perfect phase sort, 1 made a perfect experiment sort, and 1 made a perfect media sort. On the second sort, 5 of the 11 experts made a perfect media sort and 1 made a perfect phase sort. None of the novices made a perfect sort on any of the theoretical structures on either the first or second sort.

Since so few participants made sorts corresponding to any of the theoretical complete structures, we looked at their partial groupings. These are groupings all of whose members match some of the members of a group in one of the theoretical structures. This tests the assumption that participants accurately sorted according to one structure or another, although their groupings were not complete. So, for example, a grouping composed of EFMN is consistent with the $Cu(IO_3)_2$ system group even though it is incomplete because it does not include an I. However, this grouping is not accurate relative to either the precipitation experiment or the dissolution experiment because it contains one or more additional cards not consistent with these structures. The grouping EFNJ, on the other hand, would not be counted as a partial chemical grouping at all because it is not consistent with any of the chemical structures.

From the analysis of these partial groupings, it is clear that experts and novices were similar in that both organized their groups in chemical ways. In the first sort, a mean of 86.0%, $SD = 23.7$, of the experts' groupings matched at least one of the chemical structures, as did 80.4%, $SD = 16.8$, of the novice groupings. The difference is not statistically significant.

However, neither experts nor novices had a clear preference for one particular chemical structure over others. A partial grouping could be consistent with more than one theoretical structure, but we allocated a participant's grouping to one structure or another by including it in the lowest eligible structure on the hierarchy displayed in Figure 2B. For example, although the partial grouping EM is compatible with either the precipitation experiment, the $Cu(IO_3)_2$ system, or the solution phase, it would be counted as a precipitation experiment in this coding scheme. EFMN would be considered a $Cu(IO_3)_2$ system grouping, and BKEFMN would be considered a solution-phase grouping.

Of the experts' first-sort groupings, a mean of 20.6%, $SD = 32.3$, matched the experiment structure, 35.6%, $SD = 25.8$, matched the system structure, and 29.9%, $SD = 24.4$, matched the phase structure. Among the novices' groupings, a mean of 37.8%, $SD = 20.5$, matched the experiment structure, 28.2%, $SD = 19.3$, matched the system structure, and 14.4%, $SD = 14.6$, matched the phase structure. There were no significant differences in the percentages of groups explained by one chemical structure or the other for either experts or novices, or between experts and novices in the percentage of each structure used.

The differences between experts and novices in the percentage of their partial groupings that were composed of the same media (e.g., all graphs, all animations) also were not statistically significant. Of the first-sort expert groupings, a mean of 27.9%, $SD = 35.1$, matched the media structure, whereas a mean of 40.1%, $SD = 30.9$, of the novice groupings did. An analysis of the pairs of cards that appeared together in groupings found that of the eight most frequently co-occurring cards, six of the experts' pairs were of the same medium (DL, AJ, CG, FM, KN, and EI) and five of the novices' pairs were of the same medium (AJ, DL, EI, FM, and KN).

All of these same-media pairings are chemically appropriate, as are many of the larger same-media partial groupings. Although some potential same-media groupings match chemical structures, others do not. For example, A and K are both graphs, but A represents a gas-phase system and K a solution-phase system, so the grouping AK does not match a chemical structure. On the other hand, A and J are both graphs of a gas-phase system. Of the novices' same-media groupings, 90.9% also matched one of the chemical structures, as did 80.0% of the expert same-media groupings. In fact, among experts, the only nonchemical same-media groupings were made by a single individual, all of whose groupings matched the media structure rather than any of chemical structures. Excluding this person, all of the remaining expert same-media groupings matched chemical structures.

As similar as novices and experts were in the tendency to form their groupings around chemical structures, there was an important difference between them in their ability to create these groupings with multiple media. Excluding the one chemist who sorted only by media, experts used cards of more than one medium in a mean of 66.5%, $SD = 28.2$, of the chemically meaningful groupings that they created in the first sort. Novices were much less able to make these chemically meaningful multimedia groupings; only 42.0%, $SD = 29.6$, $t(18) = 1.89$, $p = .038$, of the chemically accurate novice groupings crossed media.

Furthermore, experts used *more* media than did novices in creating their cross-media groupings. Among experts in the first sort, 52.3%, $SD = 44.5$, of the chemically correct groupings used three or four different media. Only 9.0% $SD = 16.6$, $t(18) = 2.88$, $p = .005$, of the chemically correct groupings of novices used three or four different media in their first sort. Most of the novices' chemically meaningful groupings used a single medium, and the overwhelming majority of chemically correct cross-media groupings of novices consisted of only two different media.

The second sorts of both experts and novices were significantly different from their first sorts; both were less chemical in structure. Whereas a mean of 86.0%, $SD = 23.7$, of the experts' first-sort groupings were compatible with one of the chemical structures, only 48.5%, $SD = 37.4$, $t(10) = 3.73$, $p = .002$, of their second-sort groupings were compatible. As mentioned above, this difference was due in large part to the fact that 5 of the 11 experts made perfect media matches in their second sorts. For novices, a mean of 80.4%, $SD = 16.8$, of their first sort groupings matched one of the chemical structures, but only 61.7%, $SD = 20.9$, $t(8) = 1.89$, $p = .048$, of the second-sort groupings matched. The differences between experts and novices on this measure were not significant.

Reasons for Sorts. Subjects were asked to give reasons, descriptions, or names for each of their groupings. These reasons were transcribed and paired with their corresponding groups. The grouping-reason pairs were independently coded by three experienced chemistry faculty members who were blind to the expertise of the participants. They coded on the correctness of the response and the extent to which the reasons indicated that the groupings were conceptual or based on surface features. Any disagreements among coders were discussed until consensus was reached.

A grouping was coded as conceptual if it was judged that in formulating the reason, the subject supplied chemical concepts not explicitly available in the representations. A grouping was coded as being based on surface features if the reason was judged to be based only on the explicit features of the representations in the group. For example, one subject formed a group of the cards E and M and gave as a reason that "molecules were added." Representation E is a video that shows a liquid being poured into a beaker of another, bluish liquid; a white solid appears in the bottom. Representation M is an animation that shows molecules being added to a

Table 1
Examples of reasons given for groupings by experts and novices

Subjects and groupings	Reasons
Expert examples	
Subject 12	
ACJ	Gas laws
DGHL	Effects of pressure and volume
EMN	Precipitation reactions
Subject 15	
AGHJ	Gas laws
BM	Collision theory
CDL	Equilibrium
KN	Kinetics
Subject 16	
CDHKL	N_2O_4 reaction
EFMN	Precipitation reaction
Novice examples	
Subject 8	
KN	Graph of concentration
BFM	Molecules moving about
AJ	Barometric pressure
Subject 10	
EIM	Add something . . . the color is lighter . . . come together and go apart
Subject 11	
AJ	Relationship of pressure and temperature
DFLM	Reactions
EI	Diffusion of color
KN	Concentration changes with time

solution of other molecules; some of the molecules combine and settle to the bottom. This grouping and the reason that the subject gave for it (i.e., "molecules were added") were coded as surface features, because it was judged that the subject was merely reporting the information available in the surface features of both representations (i.e., the liquid being added in the video and the molecules being added in the animation). On the other hand, a second subject grouped these two cards together but gave the reason as "precipitation reactions." This was coded as conceptual because it was judged that the subject supplied chemical knowledge to the surface features to infer that the white substance in E was a precipitate forming as a result of a reaction and to group this card with M which showed an animation of molecules settling at the bottom. Table 1 displays additional examples of coded groupings.

Only the first sort is included in this analysis, since the second sort was much less chemically based. Again, the expert that made a perfect media sort was excluded. Among experts, a mean of 74.3%, SD = 21.0, of their reasons or descriptions was judged to be conceptual. Among novices, the mean was only 37.8%, SD = 19.78, $df = 18$, $t = 4.00$, $p = .0004$.

As Table 2 shows, there is a significant relationship between the use of cross-media groupings and the extent to which the groupings were coded as conceptual. Across novices and experts, 73.1% of the groupings that included different media were associated with conceptual descriptions or reasons; only 26.9% of the same-media groupings were coded as conceptual, $\chi^2(1) = 13.28$, $p = .0003$. There were no differences between experts and novices on this pattern, although novices made a greater percentage of same-media groupings than did experts, as not-

Table 2
Percent of groupings composed of the same and different media that were judged to be based on conceptual or surface reasons

Reasons	Same Media	Different Media	Totals
Conceptual	26.9	73.1	100
Surface	69.6	30.4	100
Totals	37.8	62.2	100

ed above. That is, while experts made fewer same-media chemical groupings, those that they did make were less conceptual. Conversely, while novices made fewer cross-media chemical groupings, those that they did make appeared to be more conceptually based than their single-media sorts. The conclusion is that conceptual reasoning is associated with the use of multimedia and the use of the same media is associated with surface reasoning, regardless of expertise. On the other hand, expertise is related to how often multimedia are used.

We also looked at the relationship between specific media types and the kind of descriptions or reasons given. To do this, we coded the descriptions of the same-media groupings in a second, more fine-grained way—by specific content. Four kinds of reasons were used by participants two or more times for these same-media groupings: descriptions that referred to pressure or concentration, particulate descriptions (a mention of molecules or particles precipitating), references to equations, and references to color. Other reasons or descriptions included chemical reactions, pictures, and experiments. Table 3 shows the distribution of types of reasons by type of same-media grouping. There were significant differences between media in the ways their groupings were described, χ^2 (12) = 39.56, p = .0001. Groupings that were composed entirely of animations were much more likely to be described by references to particulate matter. Groupings that were all graphs were much more likely to be described by references to relative amounts. Groupings that were all equations were most likely to be referred to as equations. References to color were more likely to be related to video groupings.

Discussion

There were clear differences between experts and novices in their ability to create chemically meaningful groupings from a diverse set of displays that used a variety of symbol systems to represent different chemical systems. As is common in studies of expertise (Glaser, 1989;

Table 3
Type of reason given for same-medium groupings

	Same-Medium Grouping				
Reason	Video	Graph	Animation	Equation	Totals
Pressure/concentration	2	8	0	1	11
Molecules/precipitation	1	0	6	1	8
Equations	0	0	0	3	3
Color	2	0	0	0	2
Other	3	3	2	2	10
Totals	8	11	8	7	34

Glaser & Chi, 1988), the chemists in this study formed larger groups than did novices. Also typical of other studies, these experts formed their groups around concepts and principles in the domain. Novices made smaller groups and were much more likely to give reasons for these groupings that merely described the common surface features of the elements in the groups.

What is distinctive about this study is that it explicitly tested experts' ability to form groups from among representations expressed in a variety of media or symbol systems. In this regard, experts in this study were much better than novices at forming chemically meaningful groupings from more than one medium. They were particularly good at creating these groups from three or four different media. Novices, on the other hand, were much more likely to form chemically meaningful groups from cards that used the same medium or symbol system. When they did create cross-media groups, novices tended to use only two different media.

Experts and novices were similar in that a large majority of the sorts of both groups were based on chemistry. Both experts and novices frequently paired same-media chemically meaningful cards together. However, medium played a particularly important role in the way novices formed their chemical groupings. A majority of the novices' chemically meaningful groupings were composed only of cards from the same medium. This result suggested that the chemical understanding of novices was bound to the common surface features of the representations. This inference is corroborated by the finding that the reasons given for making same-media groupings used terms that closely correspond to the surface features of the representations used. Animations were much more likely to be characterized by references to particles. Descriptions of groups composed of graphs were much more likely to refer to concentrations or pressure, terms that labeled the axes of the graphs. Color was more likely to be used to describe the video groupings. However, when novices formed groups across media, they were more likely to associate the groupings with deeper conceptual explanations. On these occasions, their responses were more like the responses typical of experts.

Experiment 2: Transformation Task

Subjects

The same 11 experts and 10 novices involved in the sorting task were also involved in the transformation task.

Method

Experimental Task. For the transformation task, subjects were given 15 different stimulus representations on the computer screen in one symbolic form or another and asked either to generate or to select a corresponding representation in a different form. Nine of the items required subjects to generate an equivalent representation in another specified form. For example, one item presented a video segment of an experiment and required a graph to be drawn. Another item presented an animation, and subjects were asked to generate an equation. For six of the items, a generated response would be practically impossible (e.g., the generation of an animation). For these items, participants were asked to select an equivalent response from among three that were provided in another form. For example, with one item, subjects were given a video segment and asked which of three provided animations corresponded to it.

Procedure. Subjects were given the transformation task during the same session as the sorting task. When the sorting task was completed, the transformation task was described and the administrator guided the subject through each item. The administrator presented the stimulus for each item and then asked the subject to respond to each of the items. Dynamic multiple choice responses were played simultaneously with the stimulus representation, one after the other. The subject would see the video stimulus, for example, and one of the alternative animations playing simultaneously, then the video again and the second animation, followed by the video and the third animation. The subject could repeat the viewing of any of the displays in any order.

Scoring. In scoring of multiple choice items, there was a single designated correct response. Responses to items that required participants to generate an answer were independently scored by two university chemistry faculty members blind to the expertise of the respondent. Subsequently, scoring differences were discussed and consensus was reached on the correctness of each response. Responses were judged correct if they were consistent with the display and chemically correct. For example, for one item, participants were given a video of a light brown gas that is heated in a boiling water bath and becomes darker brown. They were asked to transform a video representation to a linguistic or verbal representation; that is, they were asked to describe it. Descriptions judged to be correct included: “Heating causes reaction shown by color change,” and “Heating shifts equilibrium shown by color change.” Statements such as “Heating causes color change to get darker” and “Heating makes molecules move faster causing color change” were judged incorrect. Although the latter two descriptions are consistent with the display, they are not chemically accurate. Another item showed the same video but asked subjects to generate a graph. Subjects were scored as having a correct answer if they plotted time versus concentration and showed either NO_2 or Species A increasing in concentration over time, while either N_2O_4 or Species B decreased. Sample incorrect answers include plots of temperature versus time, color versus temperature, and so on.

Results

Overall, experts made correct transformations 74.0% of the time, mean (M) = 11.2, SD = 2.27, and novices made correct transformations 40.7% of the time, $M = 6.1$, $SD = 3.41$, $t((19) = 4.05$, $p = .0003$. However, these differences between experts and novices were not significant for the six items that asked participants to select a response from those provided. Experts gave the correct response 71.2% of the time, $M = 4.3$, $SD = 1.27$, and novices chose the correct answer 58.3% of the time, $M = 3.5$, $SD = 2.07$, $t(19) = 1.04$, $p = .16$. On the other hand, experts were correct much more often than novices on transformations that required a generated response. Experts gave correct responses on these nine items 76.7% of the time, $M = 6.9$, $SD = 1.51$, whereas novices were correct on only 28.9% of the items, $M = 2.6$, $SD = 1.58$, $t(19) = 6.39$, $p = .0001$.

There were other important differences between the two groups. Table 4 shows the percentage correct on items that provided stimuli of different representational types, regardless of the form of response. Experts scored significantly higher on items that provided stimuli in the form of videos, graphs, and animations. There were no differences between the groups on items that asked participants to respond to equations.

Table 5 shows the percentage correct on items that required responses of different representational types, regardless of the form of the stimulus. Corresponding to the above analysis,

Table 4
Mean number of items correct, by level of expertise and type of stimuli to be transformed

Type of Stimuli to Be Transformed	No. Items	Expert ($n = 11$)		Novice ($n = 10$)				
		M	*SD*	*M*	*SD*	*df*	*t*	*p*
Video into X	4	3.09	1.04	1.4	.97	19	3.84	.0005
Graph into X	4	2.6	.92	1.6	1.1	19	2.38	.01
Animation into X	3	2.4	.81	.70	.68	19	5.09	.0001
Equation into X	4	2.9	.94	2.4	1.08	19	1.16	.13

experts scored higher than novices on items that required constructed responses in the form of equations, graphs, and linguistic descriptions. The largest difference was in linguistic responses, where experts were judged to be correct twice as often as novices.

Discussion

Confirming the findings of the first experiment, the results of this study demonstrate that expert chemists are fluid in their use of a range of media to understand chemistry and express this understanding. They can easily transform chemical situations represented in one form to an equivalent expression in another form. The experts in this study were able to do so regardless of whether the situation was represented as an equation, video, graph, or animation and regardless of the form of the symbol system that the transformation was to take. They were particularly good at converting any given symbolic representation into a chemically accurate verbal description.

Novices were much less able to make transformations, at least if they involved constructing a response, as in drawing a graph or providing a verbal description. They were particularly poor at transforming animations and video into an equivalent expression in some other symbol system.

Table 5
Mean number of items correct, by level of expertise and type of response into which stimuli are transformed

Type of Response into Which Stimuli Are Transformed	No. Items	Expert ($n = 11$)		Novice ($n = 10$)				
		M	*SD*	*M*	*SD*	*df*	*t*	*p*
X into video	2	1.27	.79	1.1	.88	19	.48	.32
X into graph	3	2.0	.89	.90	.99	19	2.67	.0076
X into animation	3	2.46	.52	2.2	1.22	19	.63	.27
X into equation	3	1.8	.87	.30	.68	19	4.42	.0002
X into verbal	4	3.64	.50	1.6	.84	19	6.79	.0001

General Discussion

In this study, novices tended to sort cards so as to create small, yet chemically meaningful groups. They were not able to cross media boundaries to create larger groupings, and they had difficulty transforming chemical expressions in one medium to those of another. These data correspond to the characterization of novice understanding as unconnected “knowledge in pieces” (diSessa, 1988, 1993).

However, whereas knowledge pieces, or p-prims, in physics are inherently experiential, this study suggests that in the experientially inaccessible, submicroscopic domain of chemistry, primitive knowledge structures appear to be inherently symbolic. That is, an understanding of chemistry is built on the perceptual or surface features of physical signs (e.g., change in color) and symbolic expressions (e.g., color of balls in an animation, the labels on a graph). Novices in this study used these surface features to create an understanding of chemistry. For example, two pairs of cards that appeared often in different groupings of novices were A and J and K and N—all cards from graphs. K and N were labeled “concentration,” while A and J were labeled “pressure.” E and I were cards from videos that both showed a bluish solution in open vessels. The cards F and M were animations of the $Cu(IO_3)_2$ system that both used blue dots. These are all chemically meaningful pairings. The descriptions novices gave of these groupings suggested that they used these surface features to make their groupings rather than underlying chemical concepts: Descriptions of animations referenced particles, those of graphs referenced concentration or pressure, and color was mentioned in association with video. All of these findings suggest that the surface features of the symbolic expressions can provide the phenomenological primitives on which novices build their understanding of chemistry.

These surface elements were used by experts as well. Even though experts organized their groupings around underlying concepts and principles, there was a significant media component to their understanding. Of the 8 pairs of cards most often appearing in experts’ groups, 6 were of the same medium, including the 5 same-media pairs most often used by novices. This common use of surface features supports the contention of Smith et al. (1993) that expertise is built in a continuous way from the earlier experiences of novices. However, the difference is that whereas the understanding of novices seemed to be constrained by media and their surface features, experts were able to cross these media boundaries to connect diverse representations to underlying chemical concepts and principles.

In going beyond surface features to form large principle-based groups, experts in this study are like those in other studies of expertise that have used text to represent problem situations (Chi et al., 1981; Larkin, 1983; Larkin et al., 1980). However, the findings of this study extend notions of expertise to include the ability to see principles in problem situations, whether these are represented as equations, graphs, animations, or real-world phenomena. Chemists can see expressions with different surface features as all representing the same principle, concept, or chemical situation, and they can transform the expression of a chemical concept or situation in one form to a different form. We refer to this ability as “representational competence.”

This representational competence has important practical implications for the work of chemists. In our ethnographic research (Kozma et al., 1997), we found that chemists use multiple representations to solve significant problems in their laboratories. For example, chemists may begin their research by drawing a structural diagram of a compound that they would like to synthesize. They use this representation and their knowledge of chemical principles and procedures to design a series of chemical reactions that will rearrange atoms and bonds of the initial compounds into the desired structure of the target compound. A series of analyses is then run on the products of their experiments; these analyses result in instrument readouts [expressed in the unique symbolic markings of thin-layer chromatography plates, nuclear magnetic resonance (NMR) spectra, and so on] that provide information on the purity, composition, and structure of these products. The chemists compare specific features of these symbolic expressions (e.g., peaks in NMR spectra) with features of the diagram of the target compound (e.g., the particular composition and arrangement of atoms and bonds in the molecular structure) to make inferences about the success of their efforts. Consequently, chemists become quite practiced in transforming representations in one form (e.g., NMR spectra) into equivalent representations in another (e.g., structural diagrams).

The challenge for chemistry educators is to develop this representational competence in students of chemistry. Studies of expertise, such as the one reported here and its companion ethnographic study, are designed to inform a theory of instruction that will support the development of curricula, instructional approaches, and assessment techniques (Glaser, 1982). The identified skills of experts can be used to formulate a curriculum that supports the development of expert-like abilities in students. The ability of chemists to express their understanding in a variety of ways and the role that this ability plays in their work have important implications for designing instructional systems for undergraduate chemistry, particularly multimedia software systems. The multimedia tasks used to measure expertise can be used to monitor student progress and document learning, and this fact has implications for assessment. In the following sections, we discuss the implications this study has for chemistry curriculum, instruction, and assessment.

Implications for Chemistry Curriculum

The findings of this research identify a significant set of representational skills that seem to be a hallmark of expertise and are an important part of how chemists work and communicate with each other. The development of these skills can help students extend an understanding built on the surface features of a single representational form to one that is connected to other representational forms and includes underlying principles and concepts. The performance of experts in this study suggests that the following skills might constitute the core of a substantive curriculum of representational competence in chemistry:

- The ability to identify and analyze features of a particular representation (such as a peak on a coordinate graph) and patterns of features (such as the shape of a line in a graph) and use them as evidence to support claims or to explain, draw inferences, and make predictions about relationships among chemical phenomena or concepts.
- The ability to transform one representation into another, to map features of one onto those of another, and to explain the relationship (such as mapping a peak on a graph with the end point of a reaction in a video and a maximum concentration in a molecular-level animation).
- The ability to generate or select an appropriate representation or set of representations to explain or warrant claims about relationships among chemical phenomena or concepts.
- The ability to explain why a particular representation or set of representations is more appropriate for a particular purpose than alternative representations.
- The ability to describe how different representations might say the same thing in different ways and how one representation might say something that cannot be said with another.

Although the ability to represent chemistry in multiple ways is important, there seems to be a special role that language plays in crossing the boundaries of media and forming a semantic glue that holds different representations together. In this study, there was a strong relationship between the ability to make cross-media groupings and the ability to describe groupings in a conceptual way. Related to this pattern, chemists were better than novices at providing verbal statements that reference the underlying chemical principles and concepts of their groupings. Of all the symbol systems that chemists were able to use to express their understanding, they were most effective in transforming any representation into a chemically accurate verbal statement.

This special role for verbal ability has a particular significance for the chemistry curriculum. As often as chemistry is presented to students as a quantitative science, it may be that the development of their linguistic skills will most help students weave the various other ways of representing chemistry into a coherent understanding of chemical principles and concepts. It is language, rather than numbers, that makes chemistry a particularly human and creative endeavor (Hoffmann, 1995). Although overstated in view of the results of this study, there is still a kernel of truth in Lavoisier's statement that "We think only through the medium of words" (1965, p. xiii). Consequently, speaking and writing about chemistry should have a special place in the chemistry curriculum alongside equations, diagrams, graphs, and pictures.

Implications for Instruction

The findings from this study argue for the important role of symbolic representations in chemical instruction. However, the use of such representations should not be viewed as unproblematic aids to better science learning. Whereas instructors see chemistry in the representations that they draw, students may see only surface features—letters, numbers, and lines (Bodner, 1996). When instructors use diagrams and other representations in the classroom, they should make their reasoning explicit so students can understand the underlying meaning associated with the specific features of these expressions and see how they function to support the solution of problems in chemistry.

The development of representational competence can be fostered by explicitly engaging students in the creation of various representations and in reflection on their meaning. Students should be encouraged to represent chemical problems and solutions in a variety of ways and comment on how the representations are equivalent, how they are different, and why one form may be better at expressing a problem or solution than another for a particular purpose. Working in pairs or groups, students should be encouraged to use various representations as they talk to each other about chemistry—to describe, explain, question, and discuss their understanding as it is expressed in a variety of forms—for this is what chemists do.

Beyond the use of various representations in the chemistry classroom, the findings of this study have implications for the design of computer software that supports student understanding of chemistry. Developers of this software can use the representational and computational capabilities of computers to design symbol systems and symbolic environments that are not otherwise available in the classroom. These symbol systems can be designed such that their surface features make explicit certain aspects of chemistry that otherwise are not directly perceivable. Consequently, students can use these surface features to gain an understanding of the underlying chemistry.

For example, one of the representations we provide in our multimedia chemistry software, 4M:Chem (Kozma et al., 1996; Russell & Kozma, 1994), is an animation window in which students see molecular-level animations representing two chemical species, differing in color and composition (single brown balls and coupled white ones), in a gas-phase equilibrium. Students can manipulate variables in this simulated equilibrium system by increasing the heat or pressure. As the student heats the system, for example, the animated balls speed up and collisions more often result in the formation of brown balls than white ones. As a new equilibrium is reached, the numbers of brown and white balls remain constant in the animation window, even though they keep moving and reacting. These surface features of this representation support the notion that at equilibrium, the reaction continues to occur at equal rates in both directions.

Surface features can also be designed to help students cross media boundaries and connect multiple representations to underlying principles. By using representations with shared features (e.g., the balls in the animation are the same color as the corresponding chemical species in a video window and the corresponding lines in a coordinate graph of partial pressure), the designer can help students link various representations together. In creating these links among representations, students can add knowledge gained from one representation (such as the dynamic nature of equilibrium gained from an animation) with that from another (such as the proportional sense of equilibrium shift gained from a graph) to weave together a comprehensive and accurate understanding from the individual incomplete representations.

Implications for Assessment

For better or worse, the way learning is assessed has a profound influence on the learning behavior of students. What and how students study are significantly shaped by what they expect to see on the test. Too often, the form of a test or assignment will encourage the rote memorization of facts or the superficial manipulation of symbols. Numerous studies (Bergquist & Heikkinen, 1990; Lythcott, 1990; Nurrenburn & Pickering, 1987; Pickering, 1990; Sawyer, 1990; Smith & Metz, 1996) have demonstrated that students can give correct responses for certain types of chemistry problems but have only a limited understanding of the associated concepts. We need to develop new kinds of indicators of student learning so that studying to the test means doing a better job of learning and understanding science concepts, procedures, and problem-solving strategies (Shavelson, Carey, & Webb, 1990).

The results of this study suggest that students should be given assignments and assessment activities in which they use a variety of symbol systems to express their understanding and exercises that require them to transform symbolic expressions from one form into another, particularly into linguistic forms. Beyond multiple choice problems, test items that require open-ended verbal descriptions and the generation of pictures and diagrams will provide important additional information on students' understanding of concepts, as well as their capability to express them in various ways (Shavelson et al., 1990).

Such assessment approaches will also be more sensitive to the effects of the technology-based multimedia instructional approaches that are increasingly being used in chemistry courses (Illman, 1994). But more important, they would begin to shape the way students study and teachers teach so that our curriculum better prepares students to use the technology-based tools of scientists and acquire the skills of symbolic analysts that will be increasingly required by our information-based society in the future (Reich, 1991).

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