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The Effects of Computer Animation on the Particulate Mental Models of College Chemistry Students

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Abstract

Modern chemistry concepts have the particulate nature of matter at their core. Chemists explain most phenomena in terms of atomic and molecular models. The lack of understanding of chemistry concepts may be linked to the students' inability to build complete mental models that visualize particulate behavior. With computer animation technology, dynamic and three-dimensional presentations are possible. This study explores the effect of computer animations depicting the particulate nature of matter on college students' mental models of the chemical phenomena. A Particulate Nature of Matter Evaluation Test (PNMET) instrument was used to determine the nature of the students' visualizations and, therefore, their comprehension of the chemical concept studied. Animations were used in two treatment situations: (a) as a supplement in large-group lectures, and (b) as both the lecture supplement and an assigned individual activity in a computer laboratory. These two experimental treatments were compared to a control group. Both treatment groups received significantly higher conceptual understanding scores on the PNMET than did the control group. This increased understanding may be due to the superiority of the formation of more expertlike, dynamic mental models of particle behavior in these chemical processes.

Three levels of understanding exist for most chemistry concepts, the sensory, particulate, and symbolic levels (Gabel, Samuel, & Hunn, 1987; Johnstone, 1990, cited in Gabel and Bunce, 1991). Sensory information derived from a chemical process is explained by chemists in terms of particles, which are then translated into symbols or formulas. The particulate nature of matter (PNM) is the very essence of theoretical chemistry. Atomic and molecular behavior is an abstract construct that is used to explain most chemical concepts. We know that students have difficulty understanding concepts at the particulate level and that this is the source of many student misconceptions (Abraham, Williamson, & Westbrook, 1994; Griffiths & Preston, 1989; Haidar & Abraham, 1991; Mitchell & Gunstone, 1984; Novick & Nussbaum, 1981; Osborne, Cosgrove, & Schollum, 1982; Peterson, Treagust, & Garnett, 1989; Shepherd & Renner, 1982). The inability of students to visualize particulate behavior has been documented

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by other researchers (e.g., Ben-Zvi, Eylon, & Silberstein, 1986; Cantu & Herron, 1978; Gabel, Samuel, & Hunn, 1987; Talley, 1973; Yarroch, 1985).

The type of visualization or mental model constructed by experts differs from those of novices. Novices usually have incomplete or inaccurate models, whereas while those built by experts includes both sensory (or macroscopic) data from the physical world *and* formal abstract constructs of the phenomena (Larkin, 1983). The ultimate goal of increasing the understanding of concepts involving the PNM is served by improving the way students visualize particle behavior. How do we aid novices in building more expertlike mental models or visualizations of the particulate nature of matter?

Research has shown that visual aids might help in concept understanding (e.g., Cantu & Herron, 1978; Holliday, 1975; Talley, 1973). Static visuals have been used by Gabel and Bunce (1991), who reported increased understanding on all levels (sensory, particulate, and symbolic) when the visuals emphasized the PNM. However, static visuals fail to depict the dynamic nature of many of the processes investigated in chemistry. With the microcomputer we now have the ability to provide three-dimensional, dynamic sequences of atomic and molecular behavior in contrast to the static two-dimensional models commonly used. The dynamic qualities of animation allow a more detailed view of atomic and molecular behavior to be presented. Positive effects using animations of the PNM were seen by Zeidler and McIntosh (1990) when coupled with conceptual change strategies.

Objectives

The purpose of this article is to investigate the effect of animations on students' visualization of chemistry concepts. Specifically, the effect of computer-generated, dynamic, two- and three-dimensional graphic representations on the comprehension of concepts dependent upon the particulate nature of matter are examined. Differences in effects upon students of varying reasoning ability are also explored.

The objective of the study is to investigate the following research questions:

1. Will computer animation of concepts involving the particulate nature of matter enhance the understanding of those concepts?
2. Will computer animation of concepts involving the particulate nature of matter increase course achievement?
3. Will student attitudes toward instruction be enhanced by instruction which uses computer animation of concepts involving the particulate nature of matter?
4. Will the conceptual understanding vary with the reasoning ability of the students instructed with computer animations?

Design

Computer animation is one independent variable of the study. These sequences are graphic representations of molecular processes produced either with the Macintosh™ computer and *Macromind Director* (MacroMind, Inc. & Apple Computer, Inc., 1985–1989) software or, in the case of two animations, with the Apple II™ computer.

A second independent variable is the subject's reasoning ability. Reasoning ability is the quality of thought a student is capable of. Reasoning ability was measured by the Test of Logical Thinking (TOLT). The TOLT contains tasks measuring controlling variables, proportional reasoning, combinatorial reasoning, probabilistic reasoning, and correlational reasoning (Tobin & Capie, 1981). Internal reliability is reported for students from grade 6 through college as .85.

Construct validity is shown by a strong correlation between the TOLT and interview tasks measuring controlling variables, proportional reasoning, combinatorial reasoning, probabilistic reasoning, and correlational reasoning. The average correlation of interview tasks with the TOLT questions is .80.

Three dependent variables were measured: conceptual understanding, course achievement, and attitude toward instruction. Conceptual understanding level is one of the dependent variables. This is the degree to which a student's understanding of the concept at the particulate level corresponds to the scientifically accepted explanation of the concept. Understanding was determined by the Particulate Nature of Matter Evaluation Test (PNMET) designed to cover each unit in the study. This is an instrument requiring the students to make drawings, give explanations, or choose from multiple choices explaining chemical phenomena. This instrument is derived from those used by Novick and Nussbaum (1981), Haidar and Abraham (1991), Yarroch (1985), and Gabel et al. (1987). PNMET 5 contained 11 items covering Unit 5: Properties of Gases, Liquids and Solids, which examined the behaviors of and changes between the three phases of matter. PNMET 7 contained 7 items covering Unit 7: Reaction Chemistry, which examined dissolution of solids into aqueous solutions, the reactions of aqueous solutions, and reaction types, the three states of matter. See Figures 1 and 2 for sample items. Williamson (1992) contains the complete instruments.

"Satisfactory understanding" on the PNMET was established for each item by a panel of experts, whereas "partial understanding" scores were given to responses that included only part of the scientifically accepted answers. Scientifically incorrect responses were scored as misconceptions. "No understanding" responses are those that repeat questions, or give irrelevant or unclear responses. A similar scale has been used by other researchers (Abraham, Grzybowski, Renner, & Marek, 1992; Haidar & Abraham, 1991; Simpson & Marek, 1988; Westbrook & Marek, 1992). For statistical analysis, numeric scores of 1 were assigned to "satisfactory understanding" responses and 0 to all other categories of response. The items on each PNMET were summed to give an overall score. The items on each PNMET were summed to give an overall score. Scores for PNMET 5 ranged from 0 to 11, while scores for PNMET 7 ranged

TASK NO. 12

Particles of matter are represented by ● .
Draw a picture in the blank flask in drawing B to represent the change that occurs.

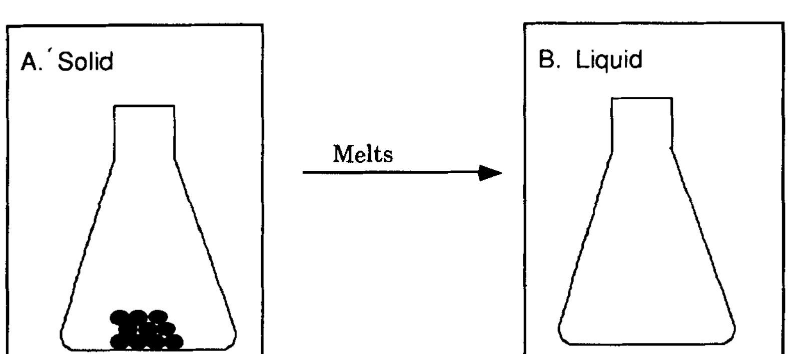


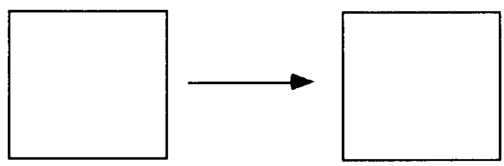
Figure 1. Task 12: PNMET for Unit 5, gases, liquids, and solids.

TASK NO. 12

Illustrate the following reaction: $2\ HI_{(g)} \longrightarrow H_{2\ (g)} + I_{2\ (g)}$
Use the symbols below in your drawing.

● = iodine atom

○ = hydrogen atom



Reactants Products

TASK NO. 13

Explain your drawings by discussing why you drew them as you did. **The explanation is as important as the drawing.**

Figure 2. Tasks 12 and 13: PNMET for Unit 7, reaction chemistry.

from 0 to 7. A panel of experts established the content validity, while percent of agreement for multiple graders on papers randomly chosen established the interrater reliability. Percentage agreement was established at $\geq 90\%$.

Course achievement is the second dependent variable. Course achievement was measured by the student's performance on the instructor's course exam. This consisted of 10 multiple-choice questions for each unit, with 5 points given for each question. Fifty points was the maximum course exam score for each unit. The content validity was established by the instructor, who is an experienced lecturer and holds a doctoral degree in chemistry. The reliability of the achievement test for each unit is assumed from the observation of consistency in exam scores in different semesters. It is also assumed that these exams are reliable because prototype test items were used.

Student attitudes toward instruction is the third dependent variable. This was measured by the Birnie-Abraham-Renner Quick Attitude Differential, the BAR (Abraham & Renner, 1983). The BAR is a 12-item semantic differential instrument. Two attitude factors have been established for the BAR. The *contentment* factor is identified as the student's degree of satisfaction with a particular unit of study. The *comprehension* factor is identified as the student's perception of progress toward understanding the concepts in a unit of study.

Procedures

The study consisted of a quasiexperimental, posttest control-group design. The treatment consisted of computer animation sequences to illuminate chemical processes at a microscopic level from two units of study: (a) Unit 5, Properties of Gases, Liquids and Solids and (b) Unit 7, Reaction Chemistry. The animation sequences were used in lecture as a visual aid and in a computer laboratory as an assigned activity.

Three treatment groups were compared: a control group, a lecture animation group, and a third group that viewed the animation sequences in both lecture and during a scheduled discussion session.

The sample consisted of students enrolled in two sections of the first semester of general chemistry at a Midwestern comprehensive university. These two sections were the only sections offered for the course and had a total enrollment of approximately 400. A single instructor taught both sections. One lecture section was randomly assigned to the experimental group, whereas the other comprised the control group. The two lecture sections received the same instruction concerning the particulate nature of matter aspects of each unit, with the exception of the use of animations. Both lecture sections received the same text presentation which included pictures, the same chalk diagrams, the same static overheads, and the same verbal explanations.

Students from each lecture section were also enrolled in one of 16 discussion/laboratory sections. Each section was taught by a graduate teaching assistant and met for 1 hour of discussion and 3 hours of wet laboratory per week. There were three discussion sections whose students all attend the experimental lecture section. The computer laboratory work was done during these discussion sections. Students viewed the animation sequences and answered worksheet questions that focused on the critical aspects of the sequences. Repeated viewing of the animations was permitted. The computer laboratory work was supervised by the investigator.

Only subjects who missed no more than one lecture and attended all of the computer sessions were included as subjects in the lecture/computer lab animation group. Only subjects who missed no more than one lecture section were included as subjects in the lecture-only animation group and the control group. Of the 124 students who qualified for inclusion in the study for the unit on Gases, Liquids, and Solids, 48, 41, and 35 were in the control group, the lecture animation group, and the lecture/computer lab animation group, respectively. A total of 124 students qualified for inclusion in the study for the unit on Reaction Chemistry. Of this number, 54 were in the control group, 38 were in the lecture animation group, and 32 were in the lecture/computer lab animation group.

Animations

Eight animations were used in six lectures during the coverage of Unit 5. These animations are summarized in Table 1. Two of these animations, Diffusion or Mixing and Ideal Gas, were developed by Dr. John Gelder from Oklahoma State University for the Apple™ computer. These were interactive, in that the lecturer could control the number of particles, pressure, tempera-

Table 1
Animations Used in Unit 5, Gases, Liquids, and Solids

Animation	Topic shown	Length
Pressure	Increased pressure gives decreased volume	2 minutes
Temperature	Increased temperature gives increased volume	2 minutes
Diffusion or mixing	Mixing of two ideal gases	interative
Ideal gas	Changes in pressure, volume, temperature, or # of particle	interactive
Phase transitions	Changes between solid, liquid and gas phase	2 minutes
Liquid-vapor equilibrium	Vapor pressure in an open vs a closed container	2.5 minutes
Intermolecular forces	Ion-dipole, dipole-dipole, and hydrogen bonding	1.25 minutes
London forces	Induced dipoles	1.5 minutes

ture, and volume. The remaining animations were produced on the Macintosh™ computer using *Swivel 3D* (Harvill, 1987–1990), which is a three-dimensional graphics program, and *Macromind Director* (MacroMind, Inc. & Apple Computer, Inc., 1985–1989), which is an animation program. Of the remaining six animations, both Pressure and Temperature were developed by the author, and London Forces and Intermolecular Forces were developed by Dr. Gelder. The final two animations were modified by the author from original creations of others, Phase Transitions from Dr. Gelder, and Liquid-Vapor Equilibrium from Dr. Mark S. Cracolice of the University of Montana.

Five animations were used in four lectures during the coverage of Unit 7. These animations are summarized in Table 2. All animations for Unit 7 were produced on the Macintosh™ computer. Two of the animations, Precipitation and Redox, were developed by the author. The remaining animations were modified by the author from those originally developed by Dr. Gelder.

Instrument Administration

Treatment lasted approximately two weeks for Unit 5. The PNMET and BAR were administered during the recitation periods following the conclusion of the treatment. Recitation sections met at various times during the week. The course exam was administered to all groups during a common evening exam time during the week following the PNMET and BAR administration.

The time frame for Unit 7 was similar to that of Unit 5, the exception being that the course exam was given two days after the last recitation section took the PNMET and BAR.

Results

A one-way analysis of variance was performed for the course exam score, the TOLT score, and each factor of the BAR for each unit of study in order to determine differences among the three treatment groups. No significant differences on any of these measures were found for either of the two units of study. A linear relationship between the PNMET score and the TOLT score supported the calculation of a correlation for each unit for all groups. A correlation of $r = 0.44$ was found for the unit on Gases, Liquids, and Solids (Unit 5) and $r = 0.52$ for the unit on Reaction Chemistry (Unit 7). Reasoning ability, therefore, explained 19–27% of the variance in

Table 2
Animations Used in Unit 7, Reaction Chemistry

Animation	Topic shown	Length
Solution	Heat of solution is thr result of making and breaking intermolecular bonds	1.5 minutes
Solution ionic	Ionic crystal dissolving	1 minute
Precipitation	NaCl dissolving, total, total ionic, & net ionic equations for NaCl + AgF	2 minutes
Temperature effects	Warmer temperatures give increased dissolving	1 minute
Redox	Na + clorine gas to form NaCl, Lewis structures used to show oxidation number changes	1.5 minutes

the conceptual understanding scores. A one-way analysis of covariance was performed for the course exam score and each factor of the BAR for each unit using the TOLT score as a covariant. This was done even when no difference among groups was detected in the TOLT scores in order to remove all effects of reasoning ability. As with the ANOVA, the ANCOVA showed no significant differences in any of the measures on either unit of study (see Table 3).

A one-way analysis of covariance was performed for the PNMET scores for each unit using the TOLT score as a covariant (see Tables 4 and 5). Again, this was done in order to remove all effects of reasoning ability. Significance at the $p < .05$ level was found for the PNMET scores for each unit. These findings imply that there is a difference in understanding by treatment group, even when the effect of reasoning ability is controlled. A Games-Howell post hoc analysis revealed that in both units, the control group had significantly lower scores than did either of the animation treatment groups. The Games-Howell analysis was chosen because it is robust to unequal cell sizes. Figures 3 and 4 graphically depict the group means for the PNMET on Unit 5 and Unit 7 respectively. Scores for PNMET 5 ranged from 0 to 11, with means of 6.438, 7.707, and 7.657 for the control, lecture animation and lecture/computer lab animation groups, respectively. Scores for PNMET 7 ranged from 0 to 7 with means of 3.481, 4.421, and 4.531 for the control, lecture animation and lecture/computer lab animation groups, respectively. There were no differences in PNMET scores between the lecture animation group and the lecture/computer lab animation group.

Effect sizes were calculated by dividing the difference in the mean of the control group and one treatment group by the standard deviation of the control group (Borg & Gall, 1989, p. 172). Effect sizes of 0.56 and 0.53 were found between the control group and the lecture animation group on Unit 5 and Unit 7, respectively. Effect sizes of 0.54 and 0.59 were found between the control group and the lecture/computer lab animation group on Unit 5 and Unit 7, respectively. Animation treatment, therefore, resulted in an increase of the mean score by about one-half a standard deviation.

Table 3
ANOVA AND ANCOVA Results on the TOLT, Course Exam, and Both Factors of the BAR for Unit 5 and Unit 7

	p value	Treatment p value	Covariant TOLT p value
ANOVA			
TOLT 5	.4221		
TOLT 7	.3032		
ANCOVA			
Course Exam 5		.5833	.0064
Course Exam 7		.3756	.0006
Bar 5, Factor 1		.5812	.6326
Bar 5, Factor 2		.3938	.1460
Bar 7, Factor 1		.9199	.0451
Bar 7, Factor 2		.6977	.0042
df =	2 between 121 within	2	1

Table 4
ANCOVA Results on PNMET 5

Type III Sums of Squares					
Source	df	Sum of squares	Mean square	*F* value	*p* value
Treatment	2	36.370	18.185	4.570	.0122
TOLT	1	112.662	112.662	28.311	.0001
Residual	120	447.524	3.979		

Dependent: PNMET 5

Group Means on PNMET 5				
	Count	Mean	Std. dev.	Std. error
Control =	48	6.438	2.268	.327
Lecture anim =	41	7.707	2.205	.344
Lecture/Computer lab = Animation	35	7.657	2.127	.360

Discussion

The TOLT results showed no differences among groups for either unit of study. This finding helps to substantiate the assumption that the groups were similar in reasoning ability. The TOLT means in this study were higher than those found for college science students by Tobin and

Table 5
ANCOVA Results on PNMET 7

Type III Sums of Squares					
Source	df	Sum of squares	Mean square	*F* value	*p* value
Treatment	2	18.891	9.445	4.210	.0171
TOLT	1	93.506	93.506	41.680	.0001
Residual	120	269.208	2.243		

Dependent: PNMET 7

Group Means on PNMET 7				
	Count	Mean	Std. dev.	Std. error
Control =	54	3.481	1.788	.243
Lecture anim =	38	4.421	1.588	.258
Lecture/Computer lab = Animation	32	4.531	1.796	.317

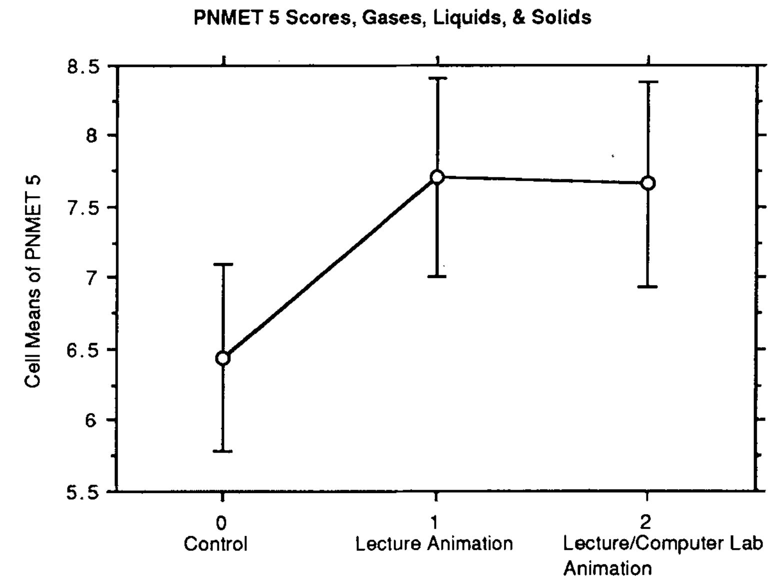


Figure 3. Group means for PNMET 5.

Capie (1981). Tobin and Capie found a mean on the TOLT of 4.4 for their sample of 247 college science students compared to means ranging from 6.46 to 7.29 for the groups used in this study. One explanation for this may lie in the fact that Unit 5 and Unit 7 occur in the last half of the course. By this point, many students who did not have the ability to do proportional reasoning or control variables have dropped the course. These abilities were required for success in

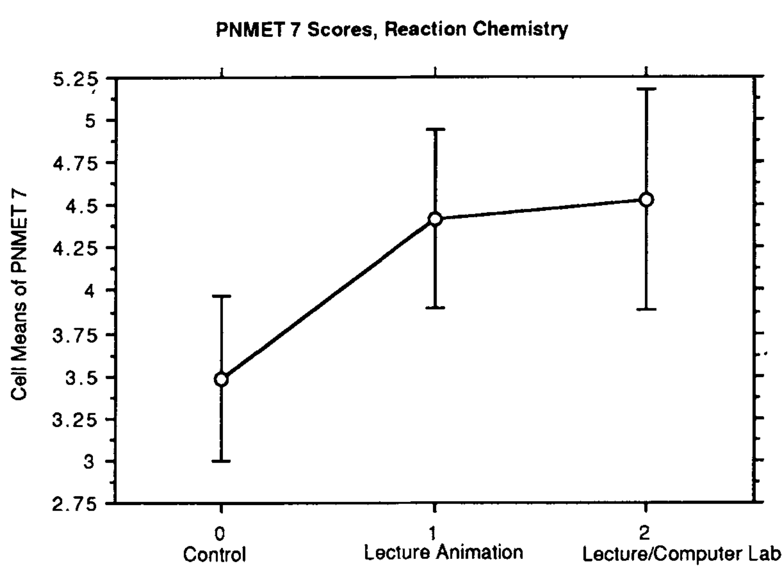


Figure 4. Group means for PNMET 7.

earlier units on stoichiometry, periodicity, and atomic structure. Because attendance was required for inclusion in the study, it may be that a proportion of students with low TOLT scores chose not to attend class regularly and were not included in the study. In studies where intact classes rather than individuals are randomly assigned, finding similarities among groups is important. The TOLT findings give evidence that the three groups in this study were similar in, at least, their reasoning ability.

The results for the BAR factors showed no differences in attitude toward instruction among groups for either unit of study. This finding implies that students' attitudes were not influenced by the "novelty" of the treatment or simply having a different treatment. This is not surprising when one considers the widespread availability of computers and the fact that the animations were shown in lecture on a screen much the same as any film or slide presentation. In addition, the duration of exposure to the treatment was very short, especially for the lecture animation group. The duration of the animations used in lecture for Unit 5, Gases, Liquids, and Solids, was approximately 18 minutes. Two of these animations were interactive and did not have a set time limit. Unit 5 was covered in six 50-minute lectures, during which approximately 6% of the instruction time was used to view animations. Animations for Unit 7, Reaction Chemistry, were used for 7 minutes of the four 50-minute lectures; therefore, 3.5% of the instruction time was spent viewing animation sequences.

The course exam showed no differences in course achievement among groups for either unit of study. Prior to initiating the study, possible gains in course achievement for the animation groups were anticipated. Analysis of the questions on the course examination revealed that a majority of the questions on the instructor-constructed test were algorithmic in nature. Current literature supports the idea that students can work algorithmic or symbolic problems using equations, *without* having a conceptual particulate understanding of the phenomena (e.g., Gabel & Bunce, 1991; Nurrenbern & Pickering, 1987; Pickering, 1990; Sawrey, 1990). The proposition that students memorized equations and the manipulation of equations that were needed to answer algorithmic problems without gaining conceptual understanding may account for the lack of difference among groups on the course examination when compared with the PNMET results.

The PNMET results showed significant differences among groups for both units of study. These differences were between the control and two animation treatment groups. The lecture animation and lecture/computer lab animation groups had similar PNMET scores. It should be noted that the inclusion criteria for this study resulted in a select sample. This select group of students was comprised of those who attended class. Only one absence from lecture was permitted in the duration of each unit, about a 2-week period. The same results might not be found with a whole-class sample.

One might expect the lecture/computer lab animation groups to have higher PNMET scores due to the prolonged treatment, which allowed for more control over the animation viewing. The lecture/computer lab group was included in the study because it was felt that the short exposure to treatment of the lecture animation group might not be robust enough to expect measurable differences. The method of animation treatment, however, made no significant difference in the students' understanding of the concepts portrayed. Students from the lecture animation group and the lecture/computer lab animation group had similar PNMET scores that were significantly higher than those of the control group. Conceptual understanding on the PNMET was related to the treatment given (control or animation) and to the TOLT score. One possible explanation might be that with the simple, basic concepts that were depicted in this study, the maximum effect was achieved with animations in lecture only. This "maximizing" effect may not occur with animations of more complex phenomena.

Another possible explanation may be that students only need to be cued to the dynamic particulate nature of these processes. The improved scores of the two animation treatment groups are surprising when one considers that the duration of each animated sequence was short (two minutes maximum). Animations were used, however, consistently throughout each unit. Both of these facts added to the possibility that students, especially those with high reasoning ability scores as in this study, may only need to be cued to internally visualize dynamic, particulate models. The effects of animations with students of lower reasoning ability scores may not be the same and should be investigated.

In addition to the short duration of the animated sequences, another factor could have had an impact on the results. The instructor who taught both the control and treatment lecture sections was very interested in visualization. As a result, many overhead transparencies and chalk diagrams depicting the particulate nature of the phenomena studied were used with both groups. Often the control group was given static visuals of the same systems that were used in the animations (e.g., a NaCl crystal dissolving in water or particles of a gas in a container of large volume versus small volume). This points to the powerful qualities of dynamic visual aids.

With very few exceptions, the responses to PNMET items were either judged satisfactory or had misconception. The "partial understanding" and "no understanding" scores were seldom used. As a consequence, the number of students holding misconceptions were inversely related to those that had satisfactory understanding. The misconception scores on the PNMET instruments were directly related to the understanding scores. As a result, the control group had significantly more misconceptions than did either animation treatment group for both units of study. The lecture animation and the lecture/computer lab animation groups were not different from each other. It is reasonable to expect that the control group, which had less understanding than the other groups, to also have more misconceptions. It is also reasonable to expect that groups with higher understanding would have fewer misconceptions.

PNMET responses indicate some interesting similarities and differences among the three treatment groups. The majority of the students from each treatment group indicated that constant motion explains why the particles of gas in a closed flask do not fall to the bottom. This choice was preferred by 88%, 80%, and 86% of the control, lecture animation, and lecture/computer lab animation groups, respectively.

In another PNMET item concerning the Gases, Liquids, and Solids Unit, the students were asked to indicate what there is between the particles of a gas. Students gave similar responses to this multiple choice question. Air was chosen for the answer by 35%, 41%, and 37% of the control, lecture animation, and lecture/computer lab animation groups, respectively. Forty-four percent of the control group, 54% of the lecture animation group, and 57% of the lecture/computer lab animation group correctly indicated that there was no material between the particles of gas. The similarity in the responses of the three groups is not surprising considering that (a) the animations did not directly address this issue, (b) the instructor's lectures that discussed this were the same for all groups, and (c) the blank space between the animated molecules could have been interpreted as containing air by students determined to cling to this notion. Novick and Nussbaum (1981) found that only 37% of their senior high and university level subjects thought the space between particles was empty. However, less than 5% of their university subjects believed that air was in the spaces, preferring vapor or oxygen and pollutants as choices.

Other similar PNMET responses among the experimental groups included answers to items concerning the Reaction Chemistry unit (Unit 7). Students did not depict hydrogen and iodine gas as diatomic, even when given a balanced equation which included diatomic formulas (see Figure 2). This error occurred in 26% of the control group, 32% of the lecture animation group, and 26% of the lecture/computer lab animation group.

On another Unit 7 item, some students indicated that when a dye diffused through water, both the dye and water molecules became the same color. This conception was held by 19%, 16%, and 12% of the control, the lecture animation, and the lecture/computer lab animation groups, respectively. While this conception did view diffusion at a particle rather than a continuous level, the color of the *macroscopic* process was attributed to the molecules. Our animations may have, in fact, reinforced this misconception that was expressed about equally by all groups. In an effort to identify atoms and molecules in an animation sequence, different shadings were used in our black and white Macintosh™ films, while different colors were used in our Apple™ animations. The use of animations, like all teaching strategies, has the potential to create or reinforce misconceptions in some students. The fact that all groups held this misconception seems to indicate that the animations were reinforcing, not creating, the misconception.

An interesting difference among the groups was found when the subjects were asked to draw a picture representing the change that occurs when a solid melts (see Figure 1). Some students chose to conserve particles between the PNMET's drawing of the solid and their drawing of the liquid. Only 56% of the control group conserved particles, whereas 73% of the lecture animation group and 77% of the lecture/computer lab animation group conserved particles. One possible explanation for this finding is that use of the animations caused the students to begin to think in particulate terms and to attend to more details concerning the behavior of particles.

Another item from Unit 5 presented students with two sealed flasks, an empty flask and a flask filled with gas particles. The students were asked to draw a representation of the substance in the empty flask after it had been liquified. Some students spontaneously and unexpectedly depicted a liquid-vapor equilibrium. Six percent of the control group, 24% of the lecture animation, and 17% of the lecture/computer animation group drew the particles in a liquid phase with one or two particles in the gas phase. The two treatment groups had viewed an animation whose length was 2.5 minutes and which depicted liquid-vapor equilibrium. It is more correct to show the liquid in a sealed container establishing an equilibrium with the gas phase. The impact of an animation of short duration is again surprising.

A final difference occurred on this same item. Some students chose to represent the liquid in continuous rather than particulate form by putting a solid line at the liquid level or by shading in the bottom of the flask. About 23% of the control group depicted a continuous view of matter, this compared to only 1 of the 41 students in the lecture animation group (2%) and none of the lecture/computer lab animation group (0%). The animation treatment seemed to encourage a particulate view of matter.

Conclusions

1. Treatment with animations may increase conceptual understanding by prompting the formation of dynamic mental models of the phenomena. The dynamic quality of animations may promote deeper encoding of information than that of static pictures. Under the dual coding theory of Paivio (1986), pictures and words activate both imaginal and verbal codes. Pictures are superior because the verbal codes for pictures are more available than imaginal codes for words, and because pictures are much more likely to be dually coded (Paivio, 1986). Animations, which could be viewed as dynamic pictures, may trigger the formation of deeper coding, thus more expertlike mental models of the phenomena.
2. Students who viewed static visuals such as transparencies or chalk diagrams may have (a) formed static mental models that failed to provide adequate understanding of the phenomena or (b) failed to form any mental model of the particulate nature of matter, and instead, were left with macroscopic views of the phenomena.

These two conclusions are based on the findings that

1. Conceptual understanding as measured by the PNMET was significantly increased for students who viewed animated sequences depicting particulate behavior. Effect sizes of about 0.5 were found. The animations provided a more scientifically correct visual model for submicroscopic processes not easily visualized. Students viewing the animations had fewer misconceptions as a consequence.
2. Students who viewed the animations held a more particulate view of matter. More conservation of particles between drawings and fewer "continuous matter" drawings were evidence of this finding.

Suggestions for Further Research

This study investigated the use of a new type of visual aid. As a result, many new questions were generated regarding the use of animations. Suggestions for further research include the investigation of (a) long-term retention of the gains from the treatment with animations, (b) the effects of prolonged animation treatment (e.g., animated sequences for all units of study dependent on the particulate nature of matter), (c) the effects of animated sequences of more complex phenomena, (d) the effects of animations with units of study other than gases, liquids, and solids or solution reaction chemistry, (e) the effects of animations with students who have lower reasoning abilities and/or are younger, (f) and, finally, the transfer of particulate models to concepts not depicted in animation treatments.

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