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ABSTRACT

This study investigated the variation of meaning that may be assigned by students to instructional symbol systems. Toward this end, student interpretations of symbols employed to represent free fall in Boxer, a computational environment designed for innovative instructional activities in math and science, were analyzed. Four classes of sixth-graders drew pencil and paper pictures of a ball in free fall three times during a four-week unit about motion. Between picture-drawing activities, students programmed simulations of motion in Boxer. Their programs were constrained according to the Boxer simulation syntax, and both dynamic and static forms of feedback reinforced this syntax. As students repeatedly drew episodes of free fall, many adopted the symbol system utilized by the Boxer environment. However, rather than uniformly copying the Boxer syntax to their pictures, students employed the observed symbols in a surprising variety of ways. Data from the pictures and student interviews suggest that the adoption of Boxer symbols was mediated by a variety of student representational ideas. Building upon the results of other studies that address interpretation of static representations, this study suggests that uniform student interpretation of computer-based dynamic representations is by no means assured. (Contains 16 references.) (Author/MES)

# The Interpretation of Symbol Schemes in a Computational Medium

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Abstract

This study investigates the variation of meaning that may be assigned by students to instructional symbol systems. Toward this end, we analyze student interpretations of symbols employed to represent free fall in Boxer, a computational environment designed for innovative instructional activities in math and science (diSessa, Abelson, & Ploger, 1991). Four classes of sixth-graders drew pencil and paper pictures of a ball in free fall three times during a four-week unit about motion. Between picture-drawing activities, students programmed simulations of motion in Boxer. Their programs were constrained according to the Boxer simulation syntax, and both dynamic and static forms of feedback reinforced this syntax. As students repeatedly drew episodes of free fall, many adopted the symbol system utilized by the Boxer environment. However, rather than uniformly "copying" the Boxer syntax to their pictures, students employed the observed symbols in a surprising variety of ways. Data from the pictures and student interviews suggest that the adoption of Boxer symbols was mediated by a variety of student representational ideas. Building upon the results of other studies that address interpretation of static representations, this study suggests that uniform student interpretation of computer-based dynamic representations is by no means assured.

## Introduction

Many visual representations, such as maps, diagrams, and coordinate graphs are central to science and mathematics. Some studies suggest, however, that students in science and mathematics are liable to misinterpret the syntax and conventions in various forms of visual representations (diSessa, Hammer, Sherin, & Kolpakowski, 1991a; Ferguson & Hegarty, 1995; Hegarty & Just, 1993; Leinhardt, Zaslavsky, & Stein, 1990; Liben & Downs, 1989; Liben & Downs, 1993). Clearly, the use of these tools during classroom instruction does not come without a price. Educators may often mistakenly assume that students interpret such representations correctly when, in fact, they do not.

In response to this challenge, Lehrer, Schauble and their colleagues (Lehrer, Jacobson, Kemeny, & Strom, 1999; Lehrer & Schauble, in press) assert that in order to learn representational syntaxes and conventions, students should invent and revise representations within a wider context of scientific argumentation. In order to insure that all students fully understand how to interpret visual representations correctly, these tools should be integrated into a social context of scientific inquiry. Without communal construction of their meaning within this wider context, representations may introduce more confusion than clarity to classroom activities.

Nemirovsky, et al. (1998) address this issue in a more general sense. They assert that one can view the world "through" a representation only after it has become completely "transparent," or the intended meaning behind it has become unambiguously accessible. Making this intended meaning accessible by all is a task of instruction. Hence, an effective use of visual representations during science and mathematics classroom activities requires that first time be spent addressing these representation's intended meanings. Considering the time constraints of a typical classroom, this time may be considered a significant overhead for instructional use of visual representations.

The above studies have focused on interpretation of static visual representations. Computer tools, in contrast, afford dynamic feedback, which can come in the form of a simulated action that unfolds in time. These dynamic representations provide a potentially useful scaffold for students, especially those who are studying forms of change. Rather than being asked to imagine change through time from one state to another, students with computers can actually observe a succession of states being played out by a programmed simulation.

Static displays of change must employ some symbolic syntax (e.g. spatial relations) in order to depict the passage of time. Dynamic representations, in contrast, afford a direct depiction of change. As a result, these dynamic representations may be more immediately "transparent" than other traditional static forms. As a result, the level of representational competence required to interpret a computer simulation of change may be less than that required to interpret traditional static depictions of change. Recent work has capitalized on this affordance of computers by designing instructional programs in calculus (Kaput, 1986; Kaput & Thompson, 1994) and physics (White, 1993; White & Fredericksen, 1998).

This study investigates whether depictions of dynamic change can provide a reliable medium for students to learn about traditional static representations of change. By integrating the static and dynamic depictions of change together, relationships between concepts of interest and the passage of time may be rendered intuitively obvious. Indeed, if the mapping between dynamic change and static syntax is clear enough, computer simulation tools may render traditional static representations of dynamic change immediately "transparent." An implication of this line of reasoning is that computer simulations may render the collective social construction of traditional static symbolic tools unnecessary.

This study addresses student learning of a static symbol system that occurs when this system is introduced in connection with student construction of dynamic representations of change in a computational medium. Do computer simulations provide a reliable link between dynamic depictions of change and static representations of them? Is the power of dynamic depictions of change sufficient to render collective construction of meaning behind static representations of change unnecessary?

## Method

### Participants

The middle school where the study was conducted serves a mostly middle-class population in a suburb of a small city. This school district serves a population which is a rural-suburban mix, and is approximately 90% white and 10% black. Two sixth-grade teachers and their students participated in this study. Both participating teachers taught two sets of students, approximately 22 students to each class. A total of 89 students participated in this study.

Both teachers are experienced in middle school instruction. One has been teaching children of this age for more than 15 years and the other for more than five years. Over the past couple of years, both teachers have taught sixth-grade science and math.

### Procedure

Design of instruction. The current study is part of a larger research project being conducted by the National Center for Improvement in Student Learning and Achievement in Science and Mathematics that is investigating middle school math and science reform. In this school, the sixth-grade science curriculum is organized by topics. Teachers have considerable freedom to choose from a list of topics for their individual science plans. Examples of topics are weather, rocks and minerals, and space science. Motion had been suggested by other teachers in the past as a topic that could be added, but a unit on motion had not yet been developed. In the context of the larger reform project, teachers and researchers collaborated to develop a motion unit. The research questions of the current study were pursued through a teaching study resulting from this collaborative effort. Instruction of the motion unit was carried out in four participating classes of students over 17 successive school days, for approximately an hour per class each day.

Collaboration involved not only initial planning, but teachers and researchers also worked together to adjust instructional plans on a daily basis. Neither teacher had experience teaching physics, and neither had mastery of many ideas in this domain. Collaboration with the research staff provided support, and the unit's development first sought to focus attention on how the students think about motion.

The instructional sequence was inspired by diSessa et al. (1991). Bruce Sherin, previously a graduate student of diSessa's, collaborated with us to generate an initial plan for the unit. We wanted to design an environment that would encourage students to theorize about patterns of speed change during motion. Toward this end, students were to invent symbolic means of representing motion, discuss their inventions, and refine their symbol systems. Our two goals were modest: First, we wanted the students to develop an understanding of some possible connections between quantitative patterns and constantly accelerated motion. Second, we wanted students to consider criteria for good representations of motion and to refine their symbol systems accordingly. We view these two goals as integrally connected. In the process of students inventing increasingly accurate and precise depictions of constant acceleration, we wanted to foster development of what diSessa et al. (1991) have termed "representational competence."

During the unit, students drew pictures of three distinct motions:

1) A book on a table is given a shove, slides for a bit, and comes to a stop.
2) A ball is held at a height of about seven feet, is released, and falls to the floor.

3) A ball is pushed across a desk, rolls across and off, falling to the floor.

Each of these motions was demonstrated by the teacher, either by pushing a book, dropping a ball, or rolling a ball off a desk. This study analyzes student pictures of free fall (number two above) only. Nevertheless, some representational ideas that were used in the free fall drawings were invented or refined while students were drawing the other motions. We will refer to student pictures of the other two motions when appropriate.

Students constructed representations of motion repeatedly in two media: student-invented drawings and Boxer motion activities. Drawings were made with paper and pencil. Students completed three sets of free fall drawings during the unit. Between these drawing activities, students programmed simulations of motion in Boxer. Boxer is an integrated programming environment designed by researchers at the University of California at Berkeley that provides the flexible construction of innovative instructional activities in math and science (diSessa, Abelson, & Ploger, 1991).

These two representational systems were utilized because each constrains the construction of representations in different ways. By using both, students were exposed to a variety of representational constraints and affordances. Representations were constructed repeatedly so that by revisiting the tasks in both media, students would have multiple opportunities to refine and improve their ideas.

First representational system: Student-invented drawings. Drawings were made with paper and pencil. This medium provides a large degree of flexibility in that virtually an infinite number of systems can be invented to represent motion. However, a paper-and-pencil medium supports only two-dimensional static depictions. This limitation introduces a challenge for students because motion is a phenomenon that unfolds in three dimensions of position across one dimension of time. Therefore, in their drawings, students had to invent ways to depict a dynamic phenomenon in a static medium.

Students drew each of the motions at three times during the unit. Between picture-drawing activities, students shared their pictures first within small groups, and then in front of the class on an overhead projector. While sharing, students were encouraged to explain both their posited patterns of speed change as well as the symbol systems they had invented to depict these patterns.

Second representational system: Boxer motion activities. Students also constructed representations in Boxer by writing simulation programs and running them. As a computational medium, Boxer afforded students the possibility of depicting motion dynamically. However, it also constrained the students to represent motion according to the program syntax. The Boxer syntax takes the form of telling an object to "jump forward so many steps." The "forward" (or "fd") command can be varied according to the number of steps entered and can be nested within a "repeat" command to make the forward jumps continue for any number of cycles. If the jumps are repeated several times and the steps are relatively small, one perceives an illusion of the object moving across the screen.

Between the first and second picture-drawing activities, students programmed hypothetical motions in Boxer. The hypothetical motions were of a girl walking and a car driving past a house. Between the second and third picture-drawing activities, students programmed the target motions they had been observing and drawing. Students were introduced to each activity through sample programs that, when run, would produce motion that clearly was not realistic. They were instructed to edit the programs to make the simulations look "as realistic as possible." Figure 1 shows the Boxer screen for the first activity of the hypothetical motions, and Figure 2 shows the Boxer screen for the second activity of programming the target motion of free fall.

[Insert Figure 1 about here]

[Insert Figure 2 about here]

One important difference between the two types of Boxer activities mentioned above is the appearance of dots in the simulations of the target motions. For example, the free fall simulation in Figure 2 shows a ball that moved downward at a constant speed, leaving a trail of dots behind it. Simulations of target motions left dots at each of the ball's "jump positions," providing a record of those positions. When a program was run, the dynamic motion illusion produced a visual impression that the programmer could compare with his or her intuitive perception of real world motions, and then, the remaining static dot representation provided a record of the illusion once it was completed.

In this way, Boxer provided integrally related dynamic and static representations of motion. The distances between successive dots corresponded both to the "forward" parameter entered by the student in the program and also to the resulting speed of the motion illusion. When the "forward" parameter was high, the illusion was of a swift motion, and the dots were left far apart. When the "forward" parameter was low, the illusion was of a slower motion, and the dots were left close together. In this way, the dots reinforced the conceptual organization of motion provided by the program syntax constraint: distance moved in equal time intervals.

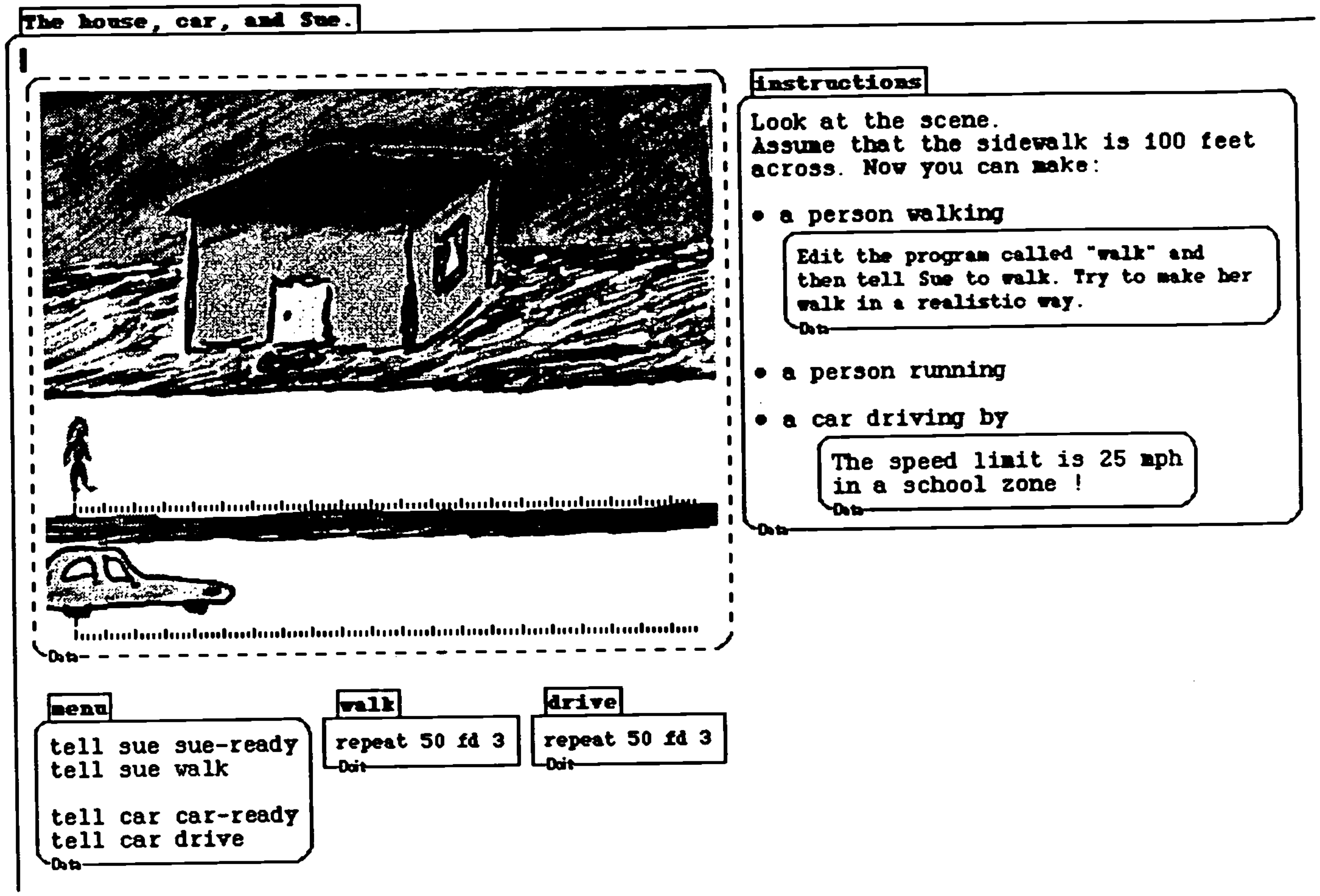
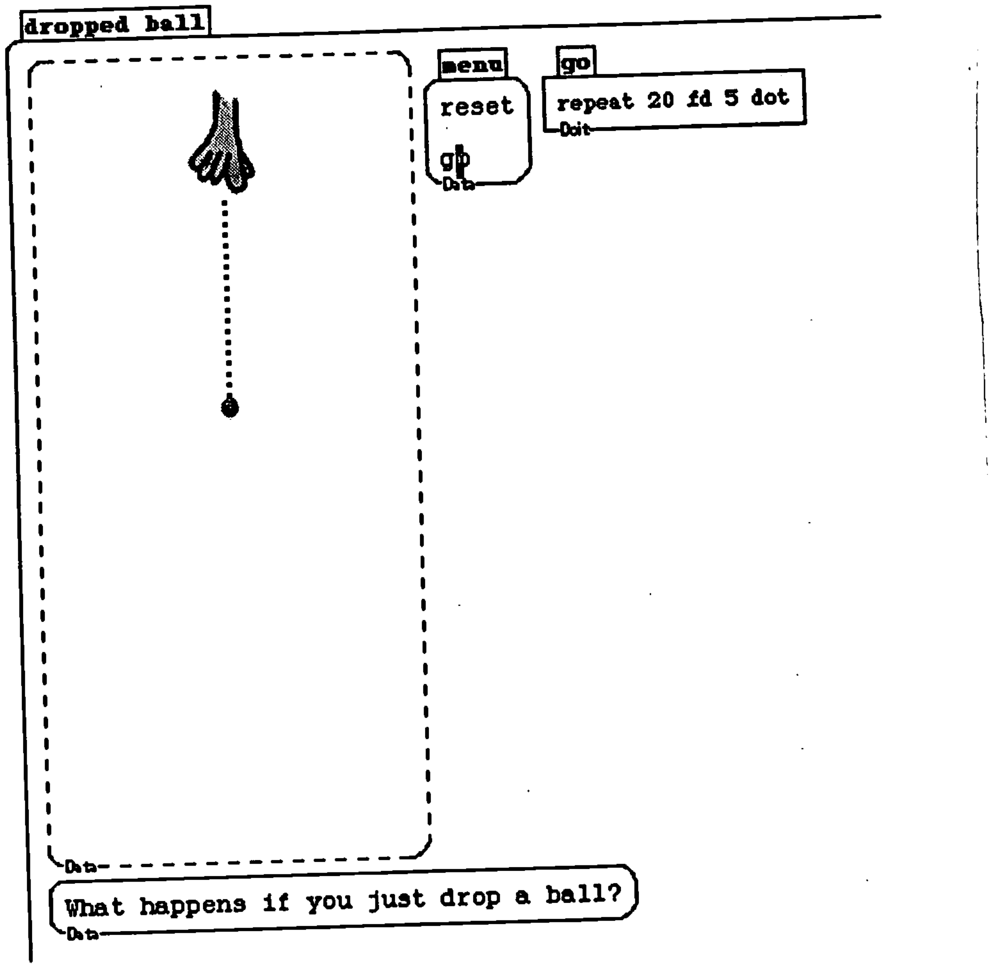

The house, car, and Sue.
instructions
Look at the scene.
Assume that the sidewalk is 100 feet across. Now you can make:
• a person walking
Edit the program called "walk" and then tell Sue to walk. Try to make her walk in a realistic way.
• a person running
• a car driving by
The speed limit is 25 mph in a school zone !
menu
tell sue sue-ready
tell sue walk
tell car car-ready
tell car drive
walk
repeat 50 fd 3
drive
repeat 50 fd 3

Figure 1



dropped ball
menu
reset
go
Data
go
repeat 20 fd 5 dot
Doit
Data
What happens if you just drop a ball?
Data


Figure 2

Data Collection

Video and field notes. Data were collected during instruction through video recordings and field notes. Two target classes (one class taught by each teacher) were videotaped daily. Detailed field notes were taken by researchers during all four of the target class sessions.

Student drawings of free fall. Student pictures of free fall were drawn at three points in time, each about six school days apart. During the first two drawing activities, students drew pictures individually and then shared their ideas within groups of three or four to produce a collaborative picture. The final drawing activity was completed individually by students as a homework assignment. The group pictures in the first and second sets were copied and analyzed, as were the individual student pictures in the third set. The number of pictures analyzed for the first, second, and third sets were 27, 33, and 89, respectively.

Student interviews. Seven target students were interviewed at three points in time during the unit. These students were chosen before the first of the three interview sessions by the teachers, three from one class and four from another. Teachers reported that they chose students so the group would represent a wide range of ability levels. Timing of the interviews coincided with the end of picture-drawing activities. Before each interview session, one author (MF) chose approximately ten student pictures from the most recent picture-drawing activity to represent a large variation of representational techniques. Interviewees were asked which picture they thought "shows the motion the best." Follow-up questions were asked until the researcher was satisfied that student criteria for good representations were understood. These interviews were audio-taped and transcribed.

## Results

This report of the results first will briefly describe some general themes in the overall development of both student pictures and Boxer programs. We provide these general themes for two reasons. First, we would like to report what was accomplished during this teaching experiment regarding our instructional goals. Second, a general report of themes will serve as background for a more fine-grained analysis of the student pictures to follow. This fine-grained analysis will focus on particular changes in student representations that address the central question of this study. For more details regarding general themes of instruction, see Ford (1999).

General Themes

Representing change quantitatively. One theme in the development of student pictures was an increase in the use of quantitative symbols. Interestingly, this development was not accompanied by a corresponding increase in reference to quantitative measurement as an empirical check on the accuracy of the representations. Rather, faced with the task to show the motion "as best you can," students increasingly opted to draft quantitative tools into their pictures simply because quantities afford a high level of expressive precision.

Students invented a variety of symbol schemes to represent changing speed during free fall. These schemes could be organized into three categories: those that express speed change patterns with quantities directly, those that express speed change in symbols that could be transformed into quantities through measurement, and those that express speed change in symbols that are not transformable into quantities. Below we briefly describe each of these groups and provide examples.

Some student pictures employed quantities of symbols to express speed change. In every case of these schemes, faster speed was represented by a greater number of symbols. For example, Figure 3 shows faster speed with an increasing number of arrows behind each successive ball.

[Insert Figure 3 about here]

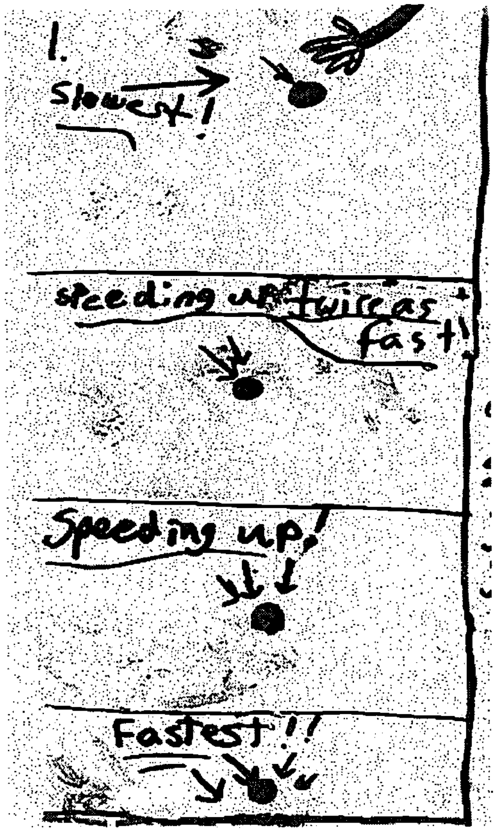



Figure 3

Other invented symbol schemes depicted greater speed by varying some measurable aspect of symbols (e.g. length or size). For example, in Figure 4, greater speed is depicted by larger size. Although such a scheme is not "quantitative" as is the scheme in Figure 3, it is certainly "quantifiable" through measure. If one wanted to transform the trend of increasing speed represented in Figure 4 into quantities, the size (e.g. horizontal width or vertical height) of each ball could be measured, and the resulting number pattern would be a quantitative expression of the information contained in the picture.

[Insert Figure 4 about here]

In contrast to both of these quantifiable schemes, other student pictures depicted changing speed without any use of quantitative tools. For example, the picture in Figure 5 depicts three speed states each represented by a symbol along the ball's path, the meaning of each symbol provided in a key. The meaning of these symbols is anchored through text in the key, and the scheme does not use quantities or quantifiable variations from state to state to depict change.

[Insert Figure 5 about here]

In the first picture set, 17.5% of the pictures expressed patterns of speed change either with quantities or quantifiable symbols. This percentage rose dramatically to 63% in the second picture set and 72% in the third.

Due to the conspicuous absence of student reference to empirical measurement throughout the duration of instruction, this trend toward quantifiable representations must have its source in representational considerations alone. Expressions of change that use quantities or quantifiable symbols are more explicit than those that employ other schemes. We believe that many students were sensitive to this quality of quantitative tools. As a result, many students chose to exploit quantity's affordance of specificity in their pictures. This result suggests that

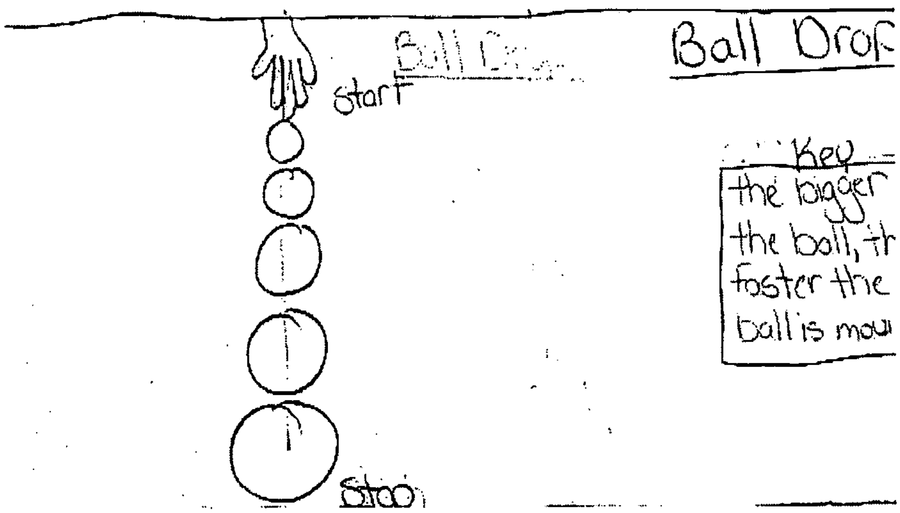



Figure 4

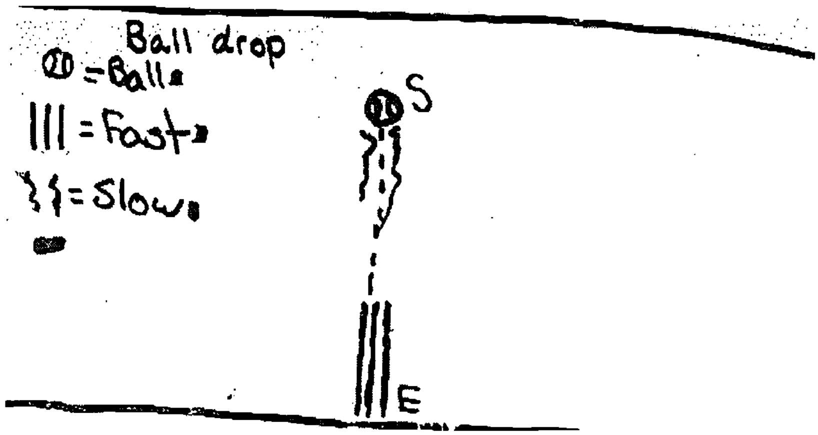



Figure 5

many students possess sufficient conceptual number resources to recognize the advantages of quantities as representational tools.

[Insert Figure 6 about here]

Representing continuity of change. Another general theme noted across picture drawing activities regards the methods students invented to depict continuity of speed change. As illustrated in Figure 5, many initial pictures utilized a set of arbitrary symbols arranged in a line along the moving object's path to depict discrete speed states. In subsequent pictures, other symbols were invented that varied according to an overall scheme. Figure 6 is a group picture from the second set of the book shove. The event is divided into three sections, each represented by a separate set of "waves." The students specify that less "wavy" depicts faster speed. Although the event is still segmented into three parts, the shapes represent speed with a variation along a common dimension: waviness.

[Insert Figure 7 about here]

The very next picture (now of free fall) drawn by one of the students in that group is shown in Figure 7. Again, the key expresses three intensities of waviness, but the event depicted is no longer segmented into three sections. The line below the ball begins very wavy and then gradually becomes less wavy.

When the picture's author presented Figure 7 to the class, her peers liked the innovation because, in their words, it shows the "smoothness" of increasing speed. In this case, "smoothness" seemed to mean continuity of speed change. Many students adopted the representational scheme of varying waviness for their subsequent pictures.

The issue of depicting continuity of speed change also was observed in the development of Boxer programs of free fall. However, in the Boxer medium, this issue was addressed in a slightly different way. In the picture-drawing activities, "smoothness" referred to the

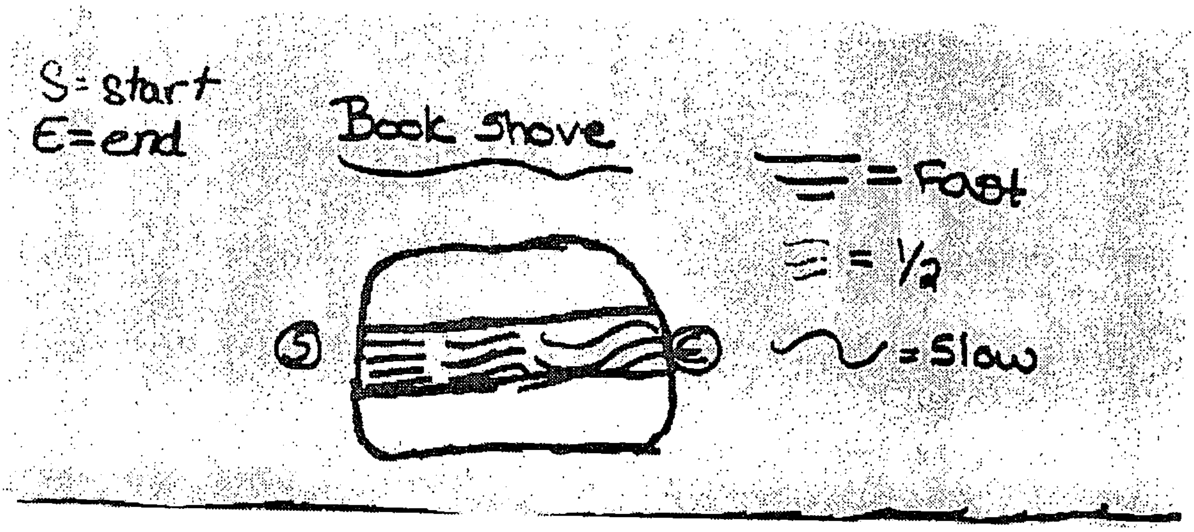



Figure 6

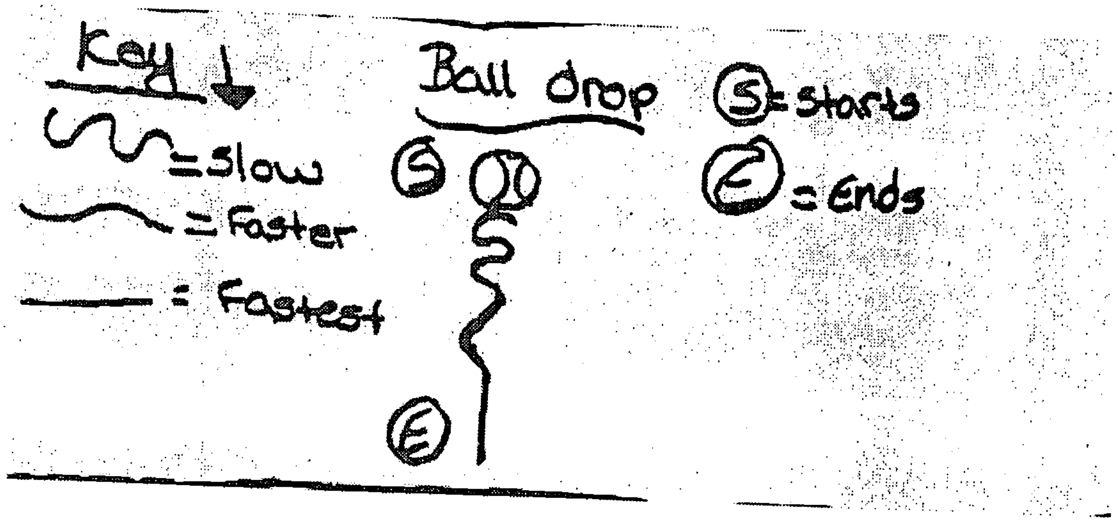



Figure 7

representation of continuous, or perhaps more accurately, seamless, speed change. In the Boxer medium, it is not possible to explicitly program seamless speed change, because Boxer programs use a discrete syntax. The object can be programmed to jump forward only a discrete number of times. Nevertheless, simulations provide dynamic feedback that can be evaluated according to the perception of "smooth," or gradual speed change. Although the simulation is discrete, a changing distance of quick jumps can be perceived to be continuous if the "forward" parameter changes gradually, and the "repeat" parameter is relatively low.

Many students initially wrote free fall simulation programs to change the speed in stages. An example of such a program is "repeat 5 forward 5; repeat 5 forward 10; repeat 5 forward 20...." After observing the simulations of several of these "stage" programs, many students said that the sudden changes in speed from stage to stage (e.g. from forward 5 to forward 10) didn't "look right." They noted that moving objects in the world speed up gradually, without "jerking" from one speed state to another. Students moved toward lower values for the repeat command and gradually increasing values for the forward command to get rid of the perceived "jerkiness." Ultimately, many students realized that instead of lowering the repeat parameter, that command can simply be deleted. Thus a common final program for the free fall activity was the program in Figure 8. Students were satisfied that their value of "smoothness" had been met with this program and ultimately decided that this program best simulated the way a ball falls in the real world.

[Insert Figure 8 about here]

<u>Relationships Between Student Representations in the Two Symbolic Media</u>

We now would like to turn to a more fine-grained analysis of student pictures in order to address the central questions of this study. Our analysis supports the following two claims. First, Boxer's representations of motion had a significant affect on student pictures. As was

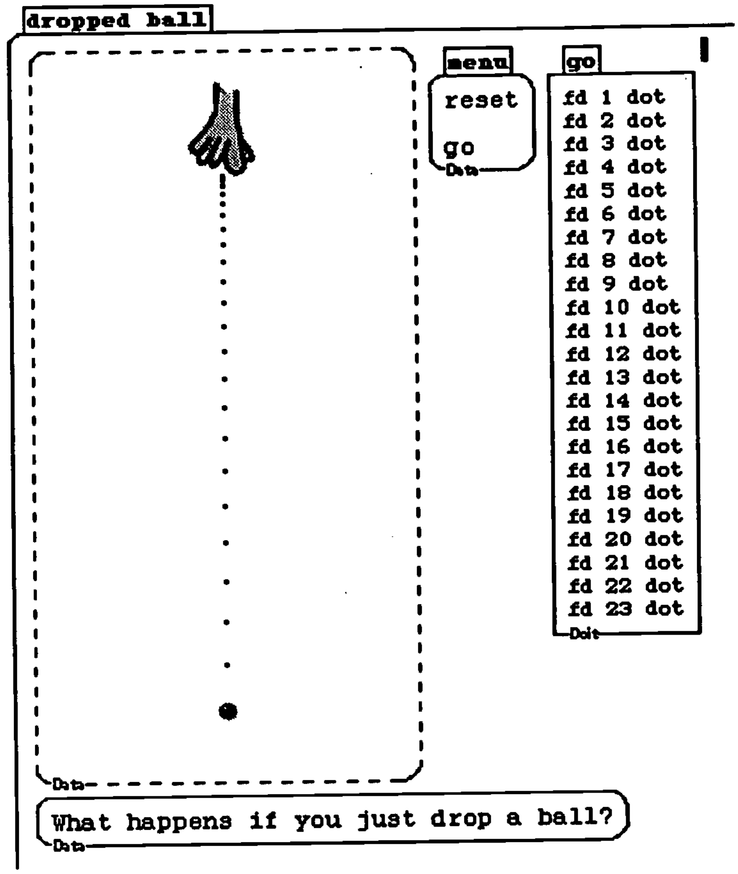

dropped ball
menu
reset
go
go
fd 1 dot
fd 2 dot
fd 3 dot
fd 4 dot
fd 5 dot
fd 6 dot
fd 7 dot
fd 8 dot
fd 9 dot
fd 10 dot
fd 11 dot
fd 12 dot
fd 13 dot
fd 14 dot
fd 15 dot
fd 16 dot
fd 17 dot
fd 18 dot
fd 19 dot
fd 20 dot
fd 21 dot
fd 22 dot
fd 23 dot
What happens if you just drop a ball?

Figure 8

previously mentioned, the Boxer syntax depicted changing speed by varying the distance between successive jump positions. In the simulations of the target motions, Boxer inserted a dot at each of these jump positions in order to make the syntax clear. Second, the effect of Boxer's "distance strategy" on student pictures was far from homogeneous. Picture analysis and interview data show that students did not interpret the meaning of the static dot representation uniformly. Rather, students integrated their own ideas about representing motion into their interpretation of the Boxer dot representations. These student ideas were found to be sufficiently robust to override the seemingly "transparent" connection between the program syntax, the resulting dynamic simulation of motion, and the static dot representation of motion.

Sudden increase in variation of distance between symbols to depict changing speed. More than a quarter (26%, n=23/89) of the students independently chose to depict changing speed in their final pictures by varying the distance between successive symbols. The relative popularity of this strategy in the final picture set is a dramatic change from just 3% (n=1/33) in the second picture set. None (n=0/27) of the initial student pictures varied the distance between symbols to represent changing speed.

The fact that so many students suddenly chose a representational strategy that had not previously emerged suggests that the Boxer simulations were the source of this strategy. We are less confident about what aspect of the simulation experience contributed most to this observed affect in student pictures. The Boxer program syntax, the resulting dynamic simulation, and the static dot representation are all in line with this "distance strategy." Because all of these aspects of Boxer simulations are aligned, it is difficult to point to any one as the sole source of the "distance strategy" appearance in student pictures. It is likely that all of these aspects of the simulation experience somehow contributed to the observed effect. Nevertheless, because the appearance of this "distance strategy" immediately follows the Boxer simulations that introduced the static dot representations, it is reasonable to point to the appearance of these dots as instrumental.

However, students did not homogeneously adopt the "distance strategy" as it had been presented in the Boxer environment. Student pictures contained representational resources adopted from the Boxer environment, but did not employ these resources according to the source syntactical meanings. Rather than simply copying what they had observed in Boxer, students adopted resources from that environment in a variety of ways. We describe the variations of student adoption of Boxer's "distance strategy" in detail below.

Reversal of Boxer "distance strategy." Of the 26% (n=23) of final student pictures that represented changing speed by varying the distance between symbols, 19% (n=18) showed greater speed by drawing successive symbols farther apart and 7% (n=5) showed greater speed by drawing them closer together. Regardless of the pattern of speed change students programmed in their simulations, the Boxer environment constrained the direction of the distance syntax: farther apart means faster. Hence a curious result of this study is the appearance in student pictures of a "closer means faster" rule that reverses the meaning of the Boxer "distance strategy." This result was observed in about 27% (n=5/23) of the pictures that varied the distance between successive objects to represent changing speed.

[Insert Figure 9 about here]

Figure 9 is a student picture that employs a "closer means faster" rule, as specified in the key. In interviews, other students chose this picture as the "best" depiction of a falling ball. They pointed out that the picture has more balls at the bottom of the ball's path than it does at the top. According to one student, such an arrangement, "makes it look like it goes faster at the bottom." Although Figure 9's author denoted in a key the syntactic meaning "closer means

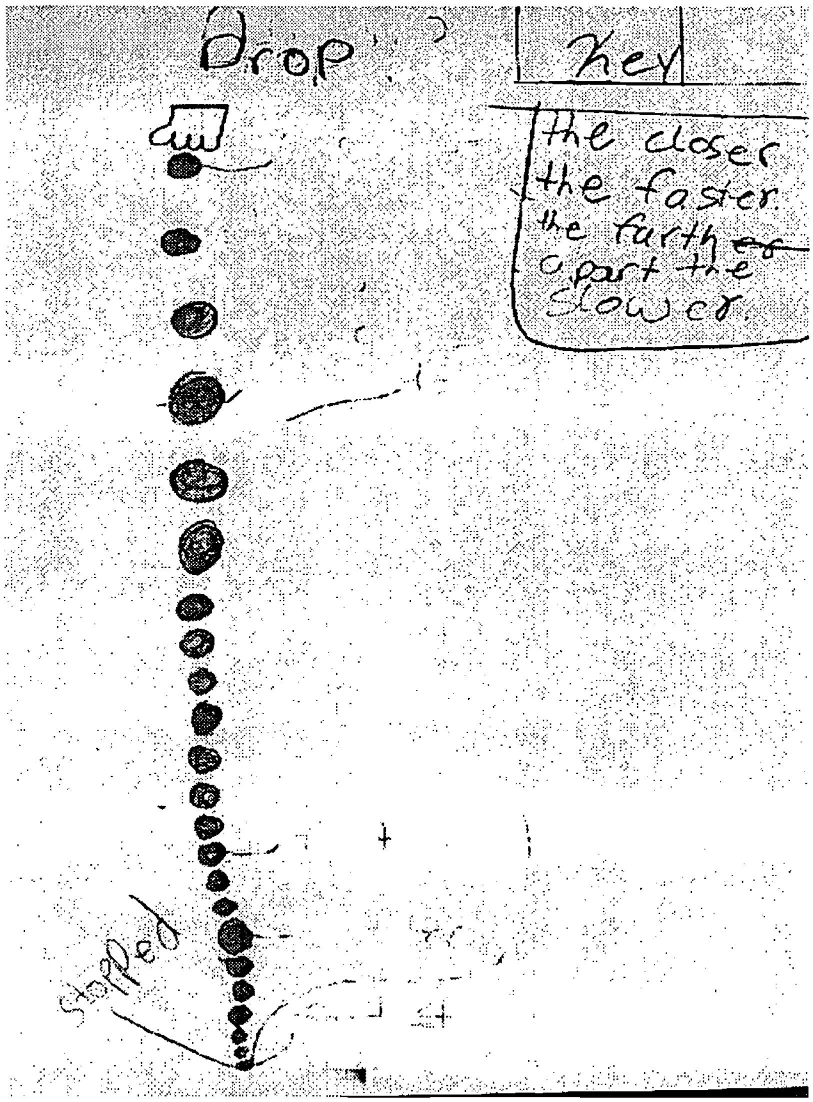

Drop
Key
the closer the faster. the farther apart the slower.
stopped

Figure 9

faster," another student's interpretation was according to a "more means faster" rule. Both rules could be used to interpret this picture consistently.

Salience of space or quantity? Reversal of the Boxer "distance strategy" in pictures could be interpreted as an issue of salience. When viewing a representation, students must choose which aspect or aspects carry the relevant information. As the interview data above illustrate, several students chose to vary the distance between successive objects, but rather than focusing on the spatial relations between them, they focused on the number of objects within a given linear extension.

As noted earlier, showing continuity of change was deemed by students as important. At the same time, as mentioned above, the use of quantities or quantifiable representations was also found to be a useful way to express patterns precisely. The simultaneous consideration of these two issues introduces a conflict. Many of the students' quantifiable schemes employ a discrete number of stages. Figure 3, for example, shows four stages, Figure 4 has five stages, and other student pictures contained more than ten stages. During discussions, students judged pictures with a greater number of stages to be better representations of motion because they made the motion seem "smoother." Nevertheless, any number of stages can not directly represent continuous change.

Reversal of Boxer's "distance strategy" in student pictures could be considered an answer to this tension between the advantages of quantities and the importance of depicting continuity of change. Figure 9 and others like it could be interpreted with salience not on the distance between symbols, but rather on the relative number of symbols within a given length. By gradually decreasing the distance between successive balls, the author of Figure 9 succeeded in expressing an increase of speed with a greater number of objects while at the same time eliminating the seams that were present in other quantitative strategies.

[Insert Figure 10 about here]

The issue of salience is more obvious in another variation of Boxer's "distance strategy." In Figure 10, a varying number of dots appears between successive balls, and the distance between the balls varies according to the number of dots between them: more dots corresponds to a greater distance between successive balls. These two variations follow a general pattern when considered in light of the textual descriptions: faster speed is represented by fewer dots and closer balls.

At first glance, this student picture is also a reversal of the Boxer syntax. However, the picture's author pointed out to one of us (MF) in an interview that the picture uses dots in the same way that Boxer simulations did. The student said that in his final "book shove" picture, he had included a key to explain his scheme. This key indicates a "fewer dots means faster" rule.

The Boxer simulation environment was intended for interpretation according to the rule, "farther dots means faster," with salience on the distance between successive objects. During both picture-drawing activities that preceded appearance of the dots in Boxer, students had overwhelmingly put salience not on the space between symbols, but on the symbols as objects themselves. In doing so, they specified what aspect of the symbols (e.g. size, length, number) carried the relevant information. The author of Figure 10 may have carried this salience into the Boxer simulation environment as well. Indeed, as successive jumps and dots get farther apart, fewer of them fit into any given length. In this way, the Boxer syntax may not only be interpreted as "farther dots means faster," but also as "fewer dots means faster." Thus, at least some misinterpretation of the Boxer dot representation may have been due to the difficulty of shifting representational salience from aspects of symbols themselves to the spatial relations between symbols.

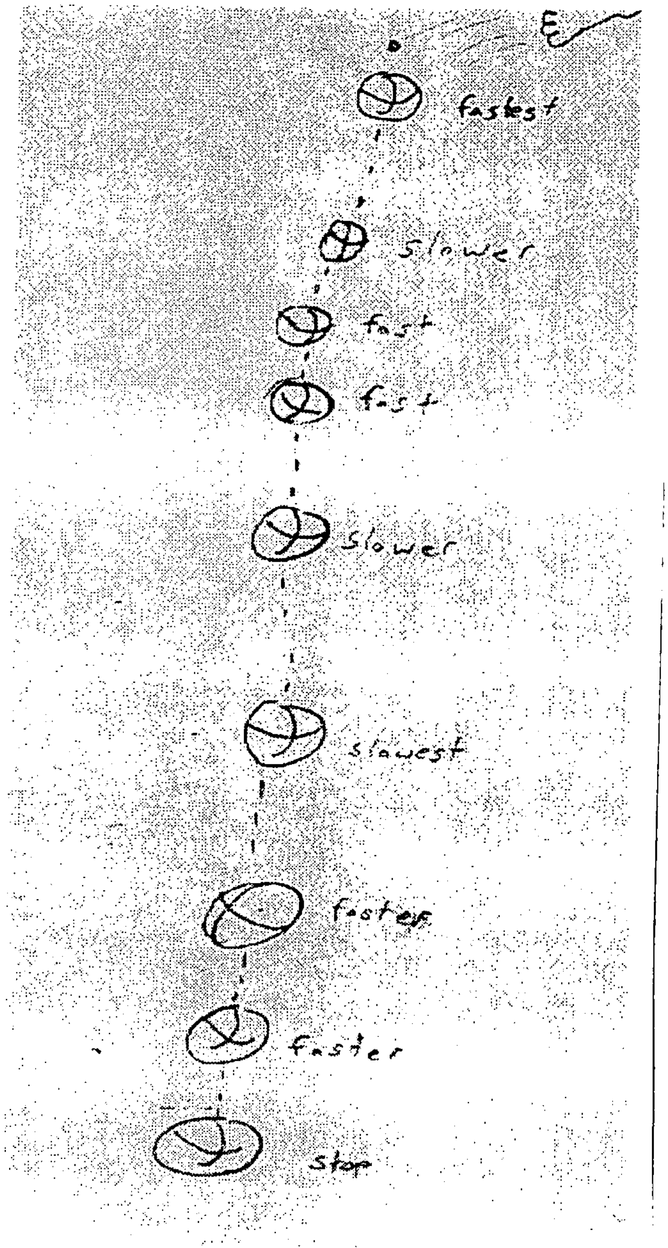

E
fastest
slower
fast
fast
slower
slowest
faster
faster
stop

Figure 10

<u>Misinterpretation of Boxer syntax.</u> Further evidence for the difficulty in shifting salience from symbols to the spatial relations between them was observed during the Boxer programming activities. At least one student initially interpreted the dots in the Boxer environment according to the rule "more means faster." As noted above, interpreting the dots in such a way results in a complete reversal of intended meaning. As the simulated motion becomes faster, successive jump positions and dots become farther apart. Hence, in order for a student to program motion according to the rule "more dots means faster," the dynamic simulation motion will be fast when it should be slow, and slow when it should be fast. In other words, the dynamic feedback would be the reverse of the motion intended. Consider the following interaction with a student programming a book-slide motion. The motion is supposed to gradually slow down to simulate a book sliding to a stop on a table.

Alan Here. (Alan shows MF initial book slide program. The simulation, rather than showing a book slowing down, has a book speeding up and coming to a sudden stop at the end of the table.)

MF Wow, so it gets faster, huh?

Alan Ye—oh, it's not supposed to get faster. No, it goes...<u>Does</u> it get faster?

MF Well, tell me, what are you thinking about that? Hold it, don't touch anything. You have—

Alan I thought this was faster (pointing to the dots).

MF Why?

Alan As they get closer... (pointing toward the closer together dots near the beginning of the book's path)

MF Because the dots are closer that would be faster?

Alan Uhhh, Oops.

MF That's okay, let's take a look at the simulation again.

(Alan runs simulation again)

Alan Oh, yeah, it is faster.

MF So it gets faster.

Alan I could just switch these around (pointing to the beginning and end commands in his program)

MF Didn't you make the same kind of point last week?

Alan Yeah, I thought closer dots means faster.

(Alan adjusts program)

During picture drawing activities that preceded this programming episode, Alan drew pictures that utilized the rule, "more symbols means faster." When he began programming, he found that the static dot representation remaining behind the simulated motion could be made to conform to this rule he had adopted for this drawings. Accordingly, he produced a program that made the dots become farther apart to signify slowing speed as the book slid across the table. However, the resulting dynamic motion simulation was the reverse of Alan's intended speed pattern. Rather than gradually slowing down, the book sped up! When his program was run, Alan completely ignored this dynamic motion simulation. For him, the meaning resided within the static dot representation alone, not within the dynamic feedback. Only after another person pointed out that the dynamic motion showed a book speeding up did Alan seem to notice the dynamic feedback.

## Discussion

The results of this study clearly show that Boxer simulation experiences did not serve as an unambiguous link between visual perceptions and static representations of motion. A quarter of the students in this study adopted ideas from the Boxer environment into their paper-and-pencil pictures. However, while almost 75% of these students adopted the "distance strategy" consistently as it had been introduced in Boxer, more than 25% of these students changed the "distance strategy" significantly. Hence, students did not uniformly interpret the static dot representation according to the intended meaning. Despite the seeming unambiguous connection between the program syntax, the mechanism of the dynamic motion illusion, and the static dot representation, many students interpreted their programming experience in ways that were not in line with the intended meaning. Is this dynamic representation of motion sufficient to unambiguously make the meaning of an aligned static representation "transparent?" The results of this study suggest that it is not.

This result was obtained from an analysis of student performance in a particular context. How well might these results generalize to other contexts? First, while the literature clearly shows that interpretation of static representations can be problematic for instruction that uses such representations, this study suggests that these difficulties may extend to dynamic representations as well.

In addition, this study suggests reasons why students interpret introduced representations in a variety of ways. We believe that the issue of salience is one that is common across many contexts. Regardless of the representational schemes being used, each student develops a stance toward the symbols that chooses aspects of salience. However, there is no guarantee that the features considered salient by a representation's author are the same features that will be considered salient by the representation's users.

Another general conclusion that can be drawn from this study is that students bring ideas from other experiences to their uses of symbolic representations, and these ideas are robust. As educators, we should not expect an introduced representation to override these ideas easily. In order for students to adopt an introduced representation along with its intended interpretation scheme, the design of instruction must explicitly address the intended interpretation scheme, and students must be provided sufficient opportunity to realign their ideas with this scheme.

We believe that the communal construction of symbolic tools' meaning is necessary for the effective use of these tools during instruction. Hence, we support the conclusions of Lehrer, et al. (in press) and others mentioned earlier. Symbolic tools can not be relied upon alone to carry the entire instructional load. This study adds the additional stipulation that this conclusion extends also to representations learned within computational environments. Representational tools, regardless of whether they are dynamic or static, must be grounded in a wider context of collaborative scientific argumentation.

More generally, we believe that the middle grades are an ideal time to introduce students to science by collaboratively developing a scientific stance toward phenomena on their own terms. In later grades, students are typically introduced to pre-packaged models that organize phenomena according to well-developed concepts and mathematical relationships. Often, these models are presented without sufficient conceptual preparation. As a result, rather than enriching students' understanding of the world they see around them, such an approach often causes a perceived disconnection between science, mathematics, and nature.

The instructional method employed in this study was designed to encourage students to develop their own scientific stance toward the phenomenon of free fall through invention and revision of visual representations. First, this approach encourages students to develop representational competence by forcing them to coordinate between multiple symbol systems invented by themselves and their peers. Such coordination is challenging, but, as illustrated in this study, raises instructionally fruitful issues that may not otherwise come up.

Second, this approach allows students in middle grades the opportunity to engage topics that have traditionally been left until high school. Students can be prepared for later introduction of more advanced models by posing questions about phenomena and inventing ways to represent these phenomena in order to address their questions. As representations are refined, instruction could be designed to "pull" students through the issues that are bound to make their representations more mathematical and empirically verifiable. By the time they get to high school, students will already have met the phenomena on their own terms, and they will be more likely to understand the problems advanced models were meant to solve. In this way, integrated development of representational competence and mathematical resources in the middle school grades can serve as a general preparation for later instruction.

In closing, we would like to note one aspect of scientific inquiry that was conspicuously lacking in student performance in this study. Students did not appeal to empirical measure to collect information for their motion representations. This result suggests that a central aspect of modern science, empirical verification, may not come naturally to students. Indeed, although scientists regularly appeal to quantitative measurements to check their theories, both children and adults often ignore this important aspect of scientific modeling. We believe that this habit of mind is not natural, but is learned over time through participation in scientific activities. Therefore, our continuing work focuses on encouraging students to glean from cases of constant acceleration information that could be used to address their invented representations and theories.

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Figure Captions

Figure 1. Boxer environment for programming walking and driving motions.

Figure 2. Boxer screen after provided program "go" was run.

Figure 3. Example of student picture that employs quantities of symbols to depict changing speed.

Figure 4. Example of student picture that employs a quantifiable change in symbols to depict changing speed.

Figure 5. Example of student picture that employs neither quantities nor quantifiable symbols to depict changing speed.

Figure 6. Student picture that represents speed change with several discrete intensities of "waviness."

Figure 7. Student picture that represents speed change with a continuous scheme of varying "waviness."

Figure 8. Boxer screen after run of program that most students agreed best simulates free fall.

Figure 9. Example of student picture that employs a "closer means faster" rule.

Figure 10. Student picture in which faster is depicted by fewer dots and closer balls.

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