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ABSTRACT

In recent years, there has been a growing interest in the use of graphing technology for the teaching of mathematics. This interest has been, in part, sparked by the recommendations of the National Council of Teachers of Mathematics (NCTM) Standards and "Everybody Counts: A Report to the Nation on the Future of Mathematics Education." The Standards call for the use of technology in the classroom; however, they also call for the integration of mathematical concepts across the curriculum. This review of the research seeks to examine both of these issues, in particular to what extent the use of graphing technology coupled with data collection devices can be beneficial in mathematics and science classrooms. The paper provides the reader with an overview and discussion of some of these results. (Contains 31 references.) (Author/NB)

How Do Students Learn with Data Collection Devices?

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In recent years there has been a growing interest in the use of graphing technology for the teaching of mathematics. This interest has been, in part, sparked by the recommendations of the *NCTM Standards* (NCTM, 1989, 2000) and, *Everybody Counts: A Report to the Nation on the Future of Mathematics Education* (NRC, 1989). The *Standards* call for the use of technology in the classroom; however, they also call for the integration of the mathematical concepts across the curriculum. This review of research seeks to examine both of these issues, in particular, to what extent can the use of graphing technology coupled with data collection devices be beneficial in the mathematics and science classrooms. This article seeks to provide the reader with an overview and discussion of some of these results.

To set the stage for this discussion, I will share an experience that illustrates some of the problems students have in understanding graphical representations. During an activity where students were asked to reproduce a distance-time graph by walking, it became exceedingly clear that the students did not understand the information that the graph was conveying. One graph that the students were asked to reproduce is shown in Figure 1. A device designed to collect data for an object's distance from a probe, Calculator-Based Ranger (CBR), was used to generate a distance-time graph in real time. By moving back and forth along a straight line, students could produce a graph resembling the given graph. However, instead students typically would walk in a path resembling the shape of the graph, going completely out of the probe's detecting range (see Figure 2). How do we deal with such misconceptions? In addition, what other misconceptions exist for student understanding of graphs?

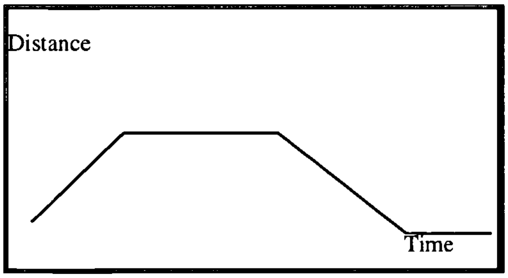

Figure 1: Distance-Time Graph for Student Investigation

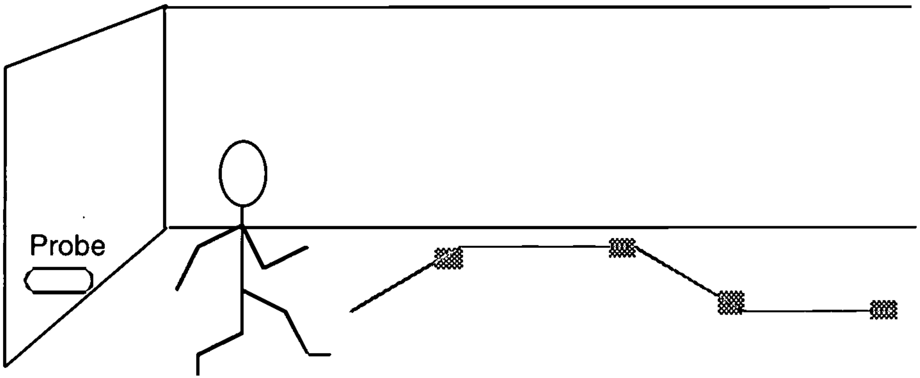

Figure 2: Path of Walker

If we wish students to have a thorough understanding of physical phenomena such as the motion of objects in space, it appears that the graphical representation has much to offer. It seems to be the consensus of researchers that the study of graphs can lead to a deeper understanding of physical concepts (Mokros & Tinker, 1987; Brasell, 1987a, 1987b; Linn, 1987; Goldberg & Anderson, 1989; and McDermott, Rosenquist,

& van Zee, 1987). However, there are many problems that students have with regard to graphing and modeling (Dunham & Osborne, 1991; Leinhardt, Zaslavsky, and Stein, 1990; Goldberg & Anderson, 1989). From research we can identify several major categories of problems.

- Difficulties in connecting graphs with physical concepts
- Difficulties in connecting graphs with the real world
- Transition between graphs and physical events
- Student discourse for building graphical concepts

The *NCTM Standards* (NCTM, 1989, 2000) call for the use of technology in the classroom; in addition, they also call for the integration of the mathematical concepts across the curriculum. This review of research seeks to examine both of these issues. To what extent can the use of graphing technology coupled with data collection devices benefit the mathematics and science classrooms?

Microcomputer-Based Laboratory (MBL), Calculator-Based Laboratory™ (CBL), and Calculator-Based Ranger™ (CBR) devices are designed to collect data via various probes and then store or feed the data into a computer or calculator. The data are then analyzed and displayed using many different representations, enabling the student to gather the data and then generate a graph either at a later time or in "real-time". Figure 3 shows the set-up of a Calculator-Based Laboratory device being used to collect voltage data for a decaying capacitor over time.

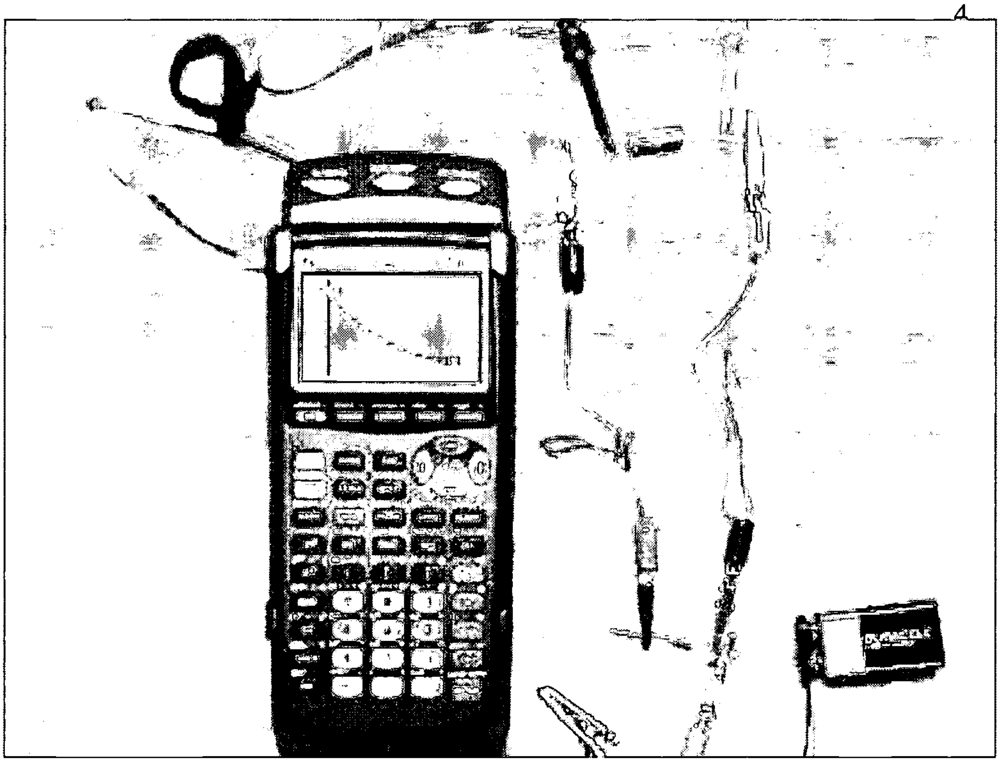

Figure 3: Capacitor Decay Set-Up With CBL2™

What aspects of graphs contribute to the misconceptions in the categories above? The research identifies several:

- *Graph as a Picture* - students do not see a graph as a relationship between variables, but rather as one object. (Dunham & Osborne, 1991; Mokros & Tinker, 1987)
- *Slope/Height Confusion* - when students are asked questions regarding rate of change of a graph, they state that the fastest change is occurring when the graph is at

its highest point. (Nemirovsky, Tierney, & Wright, 1998; Mokros & Tinker, 1987; McDermott, Rosenquist, & van Zee, 1987)

- *Graph Shape and Path of Motion Confusion* - students try to make the graph look like the physical event being observed (Goldberg & Anderson, 1989; McDermott, Rosenquist, & van Zee, 1987; Monk, 1990, 1994), (see Figures 1 & 2).

These misconceptions are addressed in the literature that follows.

Difficulties in Connecting Graphs with Physical Concepts

One advantage of Microcomputer-Based Laboratory is the ability to display the graphical representation of the data in real-time. But, to what extent does this feature play a role? Is the simultaneousness of the physical event and its graphical representation the main feature that makes MBL effective? Brasell (1987a) found that the immediacy of graph production is probably the most important feature of MBL. In fact, using different treatment groups she discovered that even a delay of 20 seconds between the ending of the physical event and the graph display makes a difference in the students' ability to link graph with physical concept.

So, is the simultaneity the only factor affecting the link between graph and physical event? Beichner (1989, 1990) suggests that this is not enough. In doing a similar study. Beichner used re-animation along with the graphical representation so that the student saw the moving object and its graph at the same time. However, this approach was not as successful as that of Brasell (1987a). Beichner's conclusion is that the ability of the student to control the environment may play a vital role in the understanding of the physical event. There may be some affective aspect of the process of experimentation that drives the student to want some sort of closure on an issue and thus actively pursue an understanding. Sometimes this is referred to as the "black box" effect. We must be careful to remember that technology alone is not sufficient.

Nakhleh and Krajcik (1991) indicate that "students using MBL activities appeared to construct more powerful and more meaningful chemical concepts" (p. 19). In this particular case, concept maps from students in a chemistry class indicated stronger connections among the concepts of acid, base, and pH. Based on their results they concluded that students construct more concepts using a MBL, but that students need careful analysis of the task, directed teaching, and class discussion to counteract the formation of inappropriate concepts. They also noted that it is reasonable to speculate that the on-screen graph allowed the MBL students to focus on what was happening rather than on trying to remember what happened while simultaneously thinking about why it had happened. The MBL maintained the graph as a constant reference while students used their short-term memory to make predictions and construct possible explanations for the graph. This finding is consistent with that of Brasell (1987b).

The application of the concepts learned by using the MBL also seems to give the students a sense of confidence in their work. Mokros (1985) reported a group of females who constructed a velocity-time graph for a cart that was accelerating. The students knew that the slope of the resulting graph had to be positive. However, when told by a teacher that the graph was incorrect, and in particular, that the line should be horizontal, they argued that their graph was indeed correct and that the slope needed to be non-zero in order for the speed to go up. This demonstrates a resolution of the slope/height confusion described earlier.

Another implication is that in order to connect graphs to physical concepts the student needs to see a variety of graphs representing different physical events (McDermott, Rosenquist, & van Zee, 1987). For example (see Figure 4), if students are taking readings to study the relationship between time and temperature of a cooling body, they will see a graph of a decreasing exponential function. Similarly, for the relationship between time and voltage of a decaying capacitor, they will see another graph of a decreasing exponential function. Observing isomorphic concepts; that is to say, concepts that are essentially the same but in different contexts; especially those that tend to be prevalent throughout nature, may aid in the abstraction of mathematical concepts.

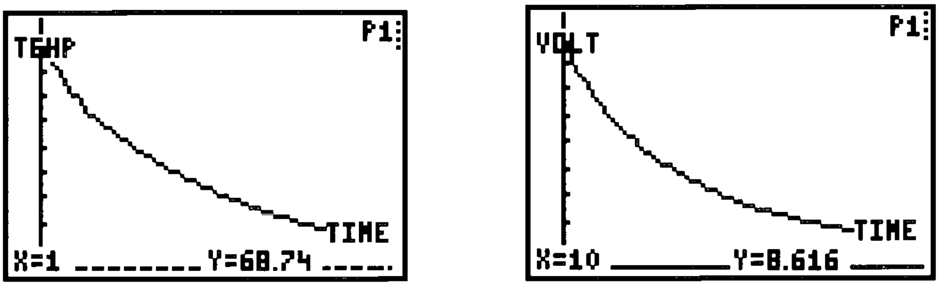

Figure 4: Exponential Model for Two Different Physical Events

Linn (1987) using MBL observed the transfer of relationships just described. Students involved in this study were dealing with the relationships of heat energy and temperature; however, the students gained considerable understanding of graphing and extended this to interpretation of motion graphs although they had not studied kinematics or motion within the graphing environment. For example, Linn states,

> As a result of studying graphs about heat and temperature, students could correctly interpret a graph showing the speed of a bicycle when the bicycle ascended a hill and then descended the hill. Prior to instruction, many students assumed that when the graph increased, the bicyclist was going up the hill (p. 8).

Bassok and Holyoak (1989) found that isomorphic concepts in the mathematics classroom allowed for the transfer of these mathematical concepts from the algebra classroom to the physics classroom. However, when physics content isomorphic to that in the mathematics curriculum was addressed in the physics classroom, the transfer of concepts from physics to mathematics did not occur. For example, if physics students study Hooke's Law that states the force on a spring is proportional to the length of its stretch, they see a linear relationship. However, the mathematical ideas learned from the physics experiment do not readily transfer to the concept of linear function when taught in the mathematics classroom. But, if linear functions are studied in a more general sense in the mathematics classroom, students tend to transfer that understanding into the physics classroom. If we use the mathematics classroom to help link concepts from other disciplines such as physics, the link of those concepts to mathematics may be aided.

Difficulties in Connecting Graphs with the Real World

The major misconceptions associated with this category are *Graph as a Picture* and *Graph Shape and Path of Motion Confusion*. In this area, students have difficulty making distinctions between the functional relationship of two variables and the visual stimuli received when observing the actual physical event.

In this case, students tend to think that the "looks" of the graph should be similar to the physical environment of the objects that produce the graph (McDermott, Rosenquist, & van Zee, 1987; Clement, 1989; Monk, 1990, 1994). If a ball is given a push on a "frictionless table" that is level (see Figure 5), the student expects the graph of the position versus time graph also to be horizontal rather than a straight line with nonzero slope (see Figure 6). Choosing the appropriate graph for the student to explore can be important in reducing this misconception. For example, if the student used MBL or CBR to examine a velocity-time graph of this same event (see Figure 7), the graph would be "flat" reinforcing the misconception. Thoughtful use of examples and nonexamples might be beneficial.

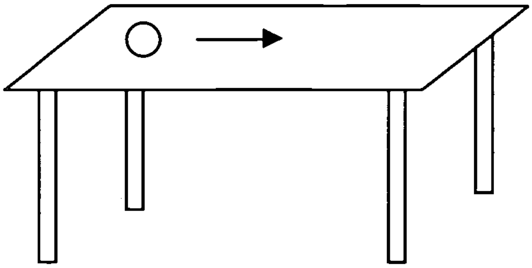

Figure 5: Ball Rolling at Constant Velocity on Tabletop

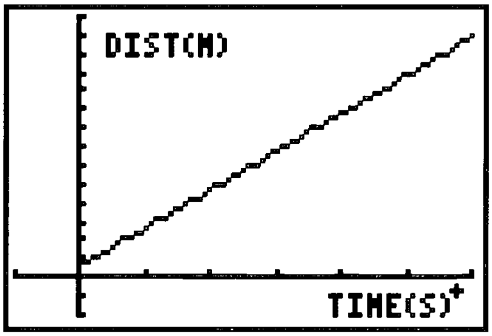

Figure 6: Distance-Time Graph of Rolling Ball on Tabletop

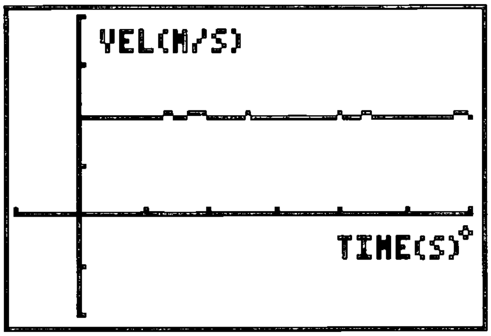

Figure 7: Velocity-Time Graph of Rolling Ball on Tabletop

In connecting a graph with the real world experiences of the student, real-time data collection seems to be the most effective. Brasell (1987b) suggests that the real-time graphing capabilities of MBL can relieve the additional information-processing demands on the student and allow for linking of the real world events and the graphical representation of these events. This stance is consistent with the findings of Nakhleh and Krajcik (1991) and Laws (1989). Brasell (1987a) suggests that a 20-second delay between event and graph production can hinder the linking of the graph with visual stimuli produced by the event. If so, then the immediacy of the graph production can give students a new way of looking at the world, as relationships, rather than as simple visual images of an event. Laws states that

> MBL stations give students immediate feedback by presenting data graphically in a manner that students can learn to interpret almost instantly. This provides a powerful link between real events that can be perceived through the senses and the graph as an abstract representation of the history of these events. Thus, MBL tools provide an ideal medium to support the development of physical intuition through direct inquiry. (p. 6).

Monk and Nemirovsky (1994) give a detailed description of a student's interaction with a physical event and the graph corresponding to the event. The student's understanding of rate of change evolves as he interacts with the device and graph in a real-time graphing environment. In this instance as well, it is the real-time graphing that facilitates the deepening of graphical understanding.

Transition Between Graphs and Physical Events

One of the most important skills required in science is the ability to leap back and forth between a graph and the physical event that the graph describes. The question is then, how can we, in practice, help students make the leap from the physical event to the graph and back? As many of us recall from methods classes, Bruner (1966) suggests a progression from enactive to iconic to symbolic representations. The CBR device, as well as any form of MBL equipped with a motion probe, makes this progression possible.

Brasell (1987b) and Mokros (1985) began with an enactive representation by using activities with MBL to challenge students to reproduce the motion for a given graph. Mokros, in particular, used the roles of "dancer" and "choreographer" with the students. The choreographer's job was to explain to the dancer what s/he should do in order to reproduce the graph given by the teacher. This activity required the students to take the graphical representation and translate it into a series of verbal directions and therefore exhibit an understanding of the various aspects of the graph. In both studies, students were significantly more successful in transferring between a physical event and the graph representing the event after having used MBL in a real-time graphing environment.

Goldberg and Anderson (1989) document student difficulty when encountering negative values for velocity as represented on a velocity-time graph, particularly with respect to direction of motion. Svec (1995) examined the students' ability to interpret an object's direction from motion graphs. He concluded that MBL significantly improved the students' ability to determine the direction of motion from a motion graph, and to qualitatively interpret distance-time, velocity-time, and acceleration-time graphs.

There is also a need for the student to be flexible when moving between different types of graphs of the same event, (e.g. position-time and velocity-time graphs of the same situation), (McDermott, Rosenquist, & van Zee, 1987). Confronting students with different types of graphs of the same event at the same time emphasizes the differences in the way the information is displayed. Also, giving the students events that are obviously different but that produce the same visual representation on a graph can help make this distinction easier to understand. For example, consider the different motion experiments producing graphs such as the following (see Figure 8). Here different physical events produced the visually similar position-time, velocity-time, and acceleration-time graphs.

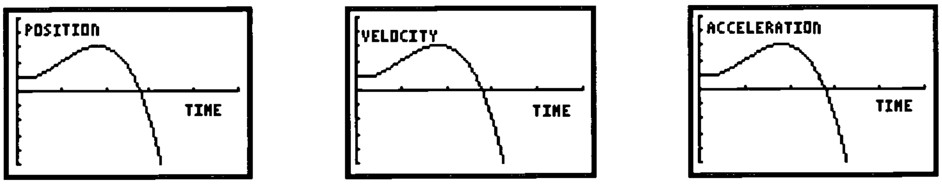

Figure 8: Differing Physical Events Producing the Same Graphical Feedback

Since the events producing the graphs are so different, the students may be concerned that the graphs appear to be the same. Having to deal with this apparent conflict between the graphs and different physical events also gives reinforcement to the way information is obtained from each graph. To find the velocity from the first graph, the student must calculate the slope at a given time. To find the velocity from the second graph, the student simply reads the graph at a given time. To find the velocity from the third graph, the student must approximate the area under the curve from time 0 to the time desired.

Likewise, it is also helpful for students to experience visually different graphs of the same event (see Figure 9). Here I have simply walked back and forth in front of a CBR producing distance-time, velocity-time, and acceleration-time graphs. The event in this case was obviously the same since I only conducted the experiment once, but the graphs are visually different. This sort of experience forces students to challenge many of the graphical misconceptions stated earlier.

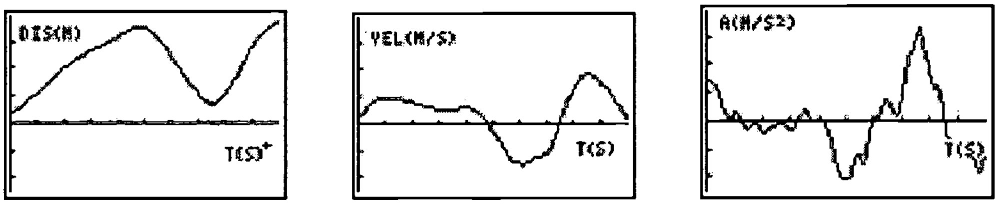

Figure 9: Same Physical Event Producing Different Graphical Feedback

Student Discourse for Building Graphical Concepts

There is evidence that pairing CBL technology with student communication can aid in the development of mathematical and scientific concepts. Svec (1995) concluded that "activities which emphasis qualitative understanding, requiring written explanations, cooperative learning, eliciting and addressing students' prior knowledge and employing the learning cycle are more effective for engendering conceptual change" (p. 23). In fact, Cooper (1995) concluded that students need to have time to rehearse their developing communication skills as part of their investigation in order to effectively construct physics concepts.

Hale (1996) looked at how students constructed and repaired conceptual understanding using discourse within a CBL environment. One drawback Hale found for using CBL in cooperative groups was that sometimes, through discourse, groups would converge on a misconception. However, she also suggests that the use of "whole" class discussion following an exploration can be used to promote further discourse while repairing any misconceptions. In support of the position that misconceptions can be valuable, Nakhleh and Krajcik (1991) suggest that the high rates of appropriate and inappropriate conceptual links exhibited by students in their study indicate that the students were positively engaged in restructuring their knowledge. We must remember that misconceptions are a part of the construction of concepts and that it is not necessarily desirable to eliminate misconceptions from the learning process. In fact, Monk and Nemirovsky (1994) suggest that students' misconceptions are not simply replaced by correct conceptions, but rather students refine their conceptions in a gradual and continuous way.

Conclusions

What then are the reasons for success of MBL? Mokros and Tinker (1987) give several reasons for why MBL is useful in connecting graphs and physical events.

- MBL uses multiple modalities
- MBL pairs events in real-time with their symbolic representations
- MBL provides scientific experiences similar to that of scientists in actual practice
- MBL eliminates the drudgery of graph production.

Thornton and Sokoloff (1990) found strong evidence for significantly improved learning and retention by students who used the MBL materials. However, they warn that the tools themselves are not enough, but that the gains in learning concepts appear to be produced by a combination of the MBL tools and appropriate curricular material that guide the students to examine appropriate phenomena. They believe that the following five characteristics of the MBL learning environment, made possible by the tools, the curriculum, and the social and physical setting, are primarily responsible for the learning gains.

- Students focus on the physical world
- Immediate feedback is available
- Collaboration is encouraged
- Powerful tools reduce unnecessary drudgery, and
- Students understand the specific and familiar before moving to the more general and abstract.

Suggestions for Classroom Use

Although the literature suggests great benefits from the use of MBL and CBL technologies, we must also consider possible problems that arise if we do not pay careful attention to how the technology is implemented. In a nine-month study of ninth grade students, Bohren (1988) found that graphing software, by constructing axes for the students covered up missing links in students' concept of scale. In addition, without proper precautions, some studies suggest that students may believe any output given by the machine even when the output gives a conclusion contrary to common sense (Lapp, 1997; Nachmias & Linn, 1987).

The use of simultaneous graph production to link a graph with a physical concept seems to be essential with motion phenomena. However, future research needs to address this issue with regard to other physical phenomena such as temperature. One might expect that the need for simultaneous graph production is not necessary for all phenomena since the human senses cannot easily distinguish among varying states all the phenomena. For example, differences in velocity seem to be more easily perceived than differences in temperature by the average person. Two people walking at, say 2 mph and 4 mph, can easily be distinguished; however, an object with temperature 2° C and another object with temperature 4° C are very difficult to distinguish. This issue needs further investigation.

Two other practices that offer promise in connecting graphs with physical events are the use of prediction and reproduction activities. Students seem to be aided when they must first communicate what they think will happen before conducting an experiment. Also, students seem to make connections if they are challenged to reproduce a given motion graph by acting it out and seeing the results in real time.

The research done in this area suggests that we can be optimistic about the benefits of MBL and CBL use in the formation of graphical concepts. However, it is too early to make any final conclusions. Further study is needed before the research community can make any definitive statements on the advantages of data collection devices.

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