The Science Teacher

ISSN: 0036-8555 (Print) 1943-4871 (Online) Journal homepage: www.tandfonline.com/journals/utst20

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To cite this article: Rebecca E. Vieyra, Colleen Megowan Romanowicz, Mina C. Johnson-Glenberg, Daniel O'Brien & Chrystian Vieyra Cortés (2024) Making Motion Meaningful: Mapping Body Movements onto Graphs, The Science Teacher, 91:6, 57-64, DOI: 10.1080/00368555.2024.2404956

To link to this article: https://doi.org/10.1080/00368555.2024.2404956

Making Motion Meaningful:

Mapping Body Movements onto Graphs

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ABSTRACT

The ability to interpret graphs is foundational to understanding many science topics, although mastering this skill can prove challenging to many students. This article illustrates how a lesson on motion graphs was implemented in physical science classes using modern smartphone LiDAR technology. It also presents the differences in accessibility and student motivation that resulted from instruction with the novel technology as compared with commercially available sonic rangers. With the help of a free, publicly-available, gamified app, students used their walking movements to match motion graphs of increasing difficulty. Students demonstrated shifts in their intuition for making graphs and showed significant gains on a pre-post assessment. Teachers observed increased enthusiasm for learning about graphs with mobile devices.

Keywords: *NGSS*; use of technology; instructional strategies; force and motion; physical science

Making sense of lines and curves on graphs is essential for everyday engagement in the world–from understanding economic trends to home electricity consumption. Students frequently struggle to make and interpret graphs (Börner, Bueckle, and Ginda 2019), and this has been a well-documented difficulty in science education for decades (Bowen and Roth 2005; Clement 1985; Glazer 2011). To tackle this challenge, our team of prior high school physics teachers, cognitive psychologists, STEM education researchers, a physicist, and a software engineer created and tested a mobile app and accompanying lesson to help learners understand motion graphs by using their body movements.

Many physical science teachers are familiar with sonic rangers—electronic devices that use sound reflections to measure the distance to objects—as they are widely available through commercial science education companies and have been demonstrated to be highly effective for learning (Brasell 1987; Redish, Saul, and Steinberg 1997). Unfortunately, these specialized devices are not available in all classrooms and cannot effectively support most at-home learning. Our team wanted to respond to calls from the National Science Foundation to harness the data revolution by helping students see that their smartphones can help them make sense of motion with high-precision data regardless of whether they are in a well-equipped lab. We also wanted the smartphone tool to provide real-time feedback to students about their kinesthetic abilities to match motion graphs, which is something that most commercial software paired with sonic rangers does not do.

The app we created is gamified: it utilizes elements of game-playing to motivate continued student engagement, such as a small reward (e.g., digital confetti), when a task is completed correctly. The app then levels up in difficulty with progressively more challenging graphs for the student to attempt to match. This approach aligns with what is known about intrinsic motivation and engagement in serious games (Malone and Lepper 1987) and learning environments (Middleton 1995; Middleton and Toluk 1999) in that it relies on *arousal,* providing students with immediate feedback on their action, and *control*, putting the measuring device directly into students' hands. The app uses sensor data to verify whether the user has achieved the goal of matching a position-time graph. The game aligns with design principles guided by decades of research, including making use of *real-world context* (such as body motion), *cognitive conflict* (providing tasks that will surprise students and challenge their assumptions), and *multimodality* (body movement, graphs, numbers, etc.) (Duijzer et al. 2019).

Research on how body motion affects learning—embodied cognition (Barsalou 2008)–supports most teachers' notions that "learning by doing" is an effective instructional strategy. While traditional instruction primarily relies on visual and verbal signals, embodiment adds sensorimotor signals, such as gesture and action, that help students process and integrate complex ideas (Goldin-Meadow 2011; Johnson-Glenberg et al. 2023). Research in science education, specifically in physics, confirms these findings (Johnson-Glenberg et al. 2016; Johnson-Glenberg and Megowan-Romanowicz 2017). Building on this research, we created an app-based activity that would help students understand motion graphs by moving their bodies–walking toward or away from a wall. We have found the approach can be more effective than more common non-embodied approaches to teaching motion graphs (Vieyra et al., 2023) and Newton's laws (Vieyra 2018), and that the use of gamification results in higher student motivation and slightly higher gains than with commercial sonic rangers and software that does not provide direct feedback (Megowan-Romanowicz et al., 2023).

Motion in the *NGSS*

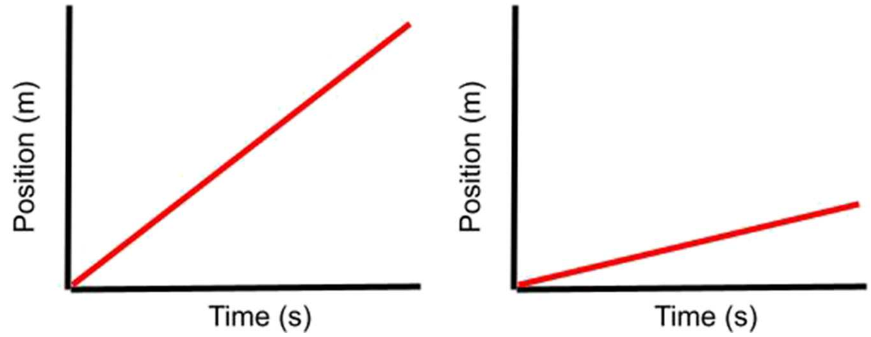
The ideas of distance and speed–and their vector equivalents displacement and velocity–are deeply embedded in all phenomena dealing with forces and interactions in the *NGSS* (HS-PS2-2: Motion and Stability: Forces and Interactions). Teachers should be especially attentive to addressing these concepts as they build up to the performance expectations, especially if students did not master them in earlier grades.

Graphs can serve as tools for understanding motion, laying a foundation for more advanced scientific thinking and mathematical modeling. For example, it is common to provide students with graphs like those in Figure 1 and ask what they represent.

Students often interpret these graphs as two-dimensional pictures (Beichner 1994; Motlhabane 2016; Trowbridge and McDermott 1981), rather than as representations of position

FIGURE 1

(a) Graph of an object moving away from the origin with a relatively fast constant speed. (b) Graph of an object moving away from the origin with a relatively slow constant speed.



through time. Students also struggle when comparing relative shapes, especially for objects moving toward–rather than away from–the point of origin (Table 1).

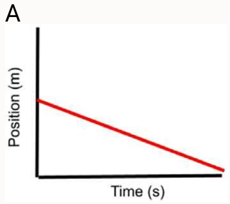
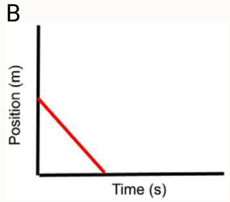
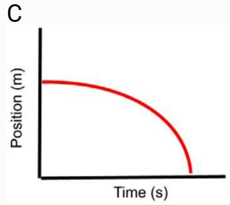
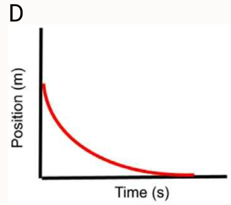
Student understanding can be further complicated when they are introduced to velocity that changes over time–i.e., acceleration. Without proper grounding, the term *acceleration* can also introduce difficulties, as it may represent speeding up (as in graph C) or slowing down (as in graph D). Only by having a deep understanding of the physics underlying these questions can students master Newton's Laws.

Matching the graphs with LiDAR motion visualizer

Research shows that simply instructing students how to read graphs, such as those above, is ineffective when students' intuition

TABLE 1

Motion graphs showing movement away from the point of origin.

Motion Graph	A 	B 	C 	D 
Incorrect Interpretation (Common inaccurate or incomplete student ideas before instruction).	An object speeds up as it goes down a hill.	An object speeds up even faster as it goes down an even steeper hill than in graph A.	An object moves along a shallow incline and then falls down a "cliff."	An object goes down a steep slope and then slows down as it reaches the bottom (like a "slide").
Correct Interpretation	An object moves at a slow, constant speed toward its starting point.	An object moves at a fast, constant speed toward its starting point.	An object moves toward its starting point, first slowly, and then speeding up.	An object moves toward its starting point, first quickly, and then slowing down.

leads them in another direction (DiSessa 1993). A more evidence-based approach is to help students build a new form of intuition and to do so in an embodied way. Our approach is to introduce motion by providing adolescent students with a scaffolded set of motion graphs on their smartphones and having the students match them with their body motions.

We created a gamified learning experience, *Motion Visualizer*, within the free and widely-used *Physics Toolbox Sensor Suite* app (Vieyra Software 2024; Vieyra et al. 2015) for modern iOS devices that use the Light Detection and Ranging (LiDAR) sensor. The LiDAR sensor, available on the iPad Pro as well as on iPhone 12-15 Pro/Pro Max, and expected on all later versions, emits an array of infrared light beams. When they hit a surface and return, the smartphone knows how far away the surface is. This sensor was designed to enhance portrait photography, but it also works as a high-precision distance measurement tool. When students use *LiDAR Motion*, they can point their device at a stationary, flat surface (e.g., a wall), which is defined by the app as position = 0 m, and move toward and/or away from the wall in a straight line perpendicular to the wall. As they walk, they see their motion plotted on a position-time graph.

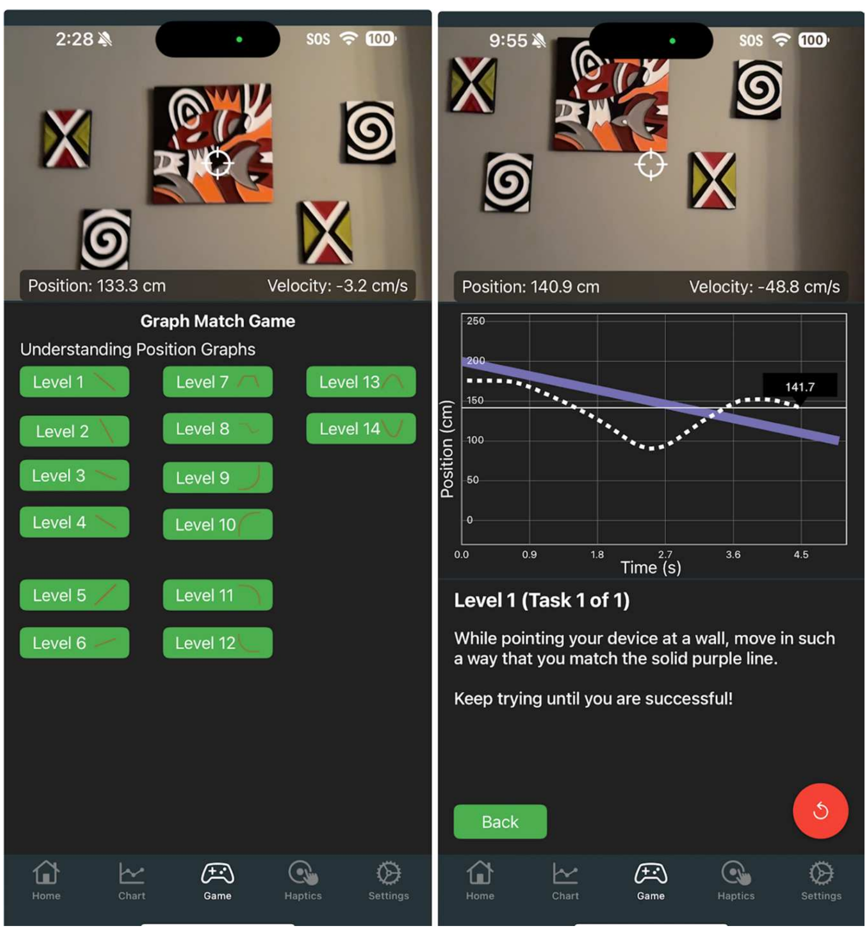
The game contains 14 levels (Figure 2a), progressing from constant speed to multi-segment motion and acceleration, with tasks that help students compare differences in motion. Within each task, students must move toward and/or away from a wall. Their motion is plotted with a dotted line, and their goal is to match the solid, purple line (Figure 2b). When students reasonably match their dotted line motion to the solid line, they are rewarded with digital confetti, and the game registers that they completed the task.

Testing LiDAR motion visualizer in schools

In collaboration with students and their teachers in high-diversity public secondary schools, we used this gamified lesson in physical science classes in two secondary schools: (1) one classroom in the southwest U.S. (97% free or reduced lunch rates, and a high percentage of English-language learners), and (2) two classrooms in

FIGURE 2

(a) Game interface with camera view pointed at a painting on the wall (above) and the 14 motion graph tasks (below). (b) Game interface showing walked motion (dotted line).



the northeast U.S. (35% free or reduced lunch rates, and a high percentage of special needs learners). Using the app, we designed a sequence of activities to be completed in approximately 90 minutes. A student worksheet, which provides students with a place to reflect on each of the tasks after they complete them, is accessible from https://www.lidar-motion.net/lesson-ideas.

The lessons took place after students understood the ideas of position and distance, but before being introduced to motion graphs. After telling students they would be playing a game, we showed them the app, allowing them to click through a simple tutorial. Then they found a flat wall with about 10 feet of clear, debris-free walking space perpendicular to the wall. Students worked in pairs or groups of three to engage in free exploration, taking turns to see how their body motion was represented on the position-time graph (Figure 3).

Students then worked at their own pace, taking turns with partners, to complete all of the tasks and reflect on holistic questions that helped them to solidify their understanding (see Table 2). At several points throughout the activity, students came back together and shared their ideas on large pieces of paper (Figure 4), helping the class to understand how different shapes on motion graphs represented different types of movement.

Teachers and students responded favorably in both classrooms. The teacher of the southwest region classroom was excited to try this new approach. Observing her students get up and move around the classroom for the activities, she noted high enthusiasm: "Students loved the ability to practice with their bodies. That sticks with them. It makes more sense to them if they are doing an action." Students were generally on task, collaborated to complete the tasks (Figure 5), and were reluctant to pause their engagement when asked to return to their seats.

Most notable was the impact of the activity on students who normally struggled in class. The teacher shared, "There's a student in class that probably should be identified as having special needs, but is not. She was in one of the groups that finished the tasks first and began to help the other teams. I have proof of the fact that it boosted at least that student's confidence. Normally, students like her are the ones who struggle with everything math and science, and you can tell on their faces when they are not having it. This time, when engaging with others, she was able to say, 'Let *me* help *you*.'" The teacher also appreciated the connections that the activity helped her to bridge math and science concepts–something she finds that students often do not achieve on their own.

FIGURE 3

Students walk back and forth from a lab cabinet as they try to match a multi-segment graph.

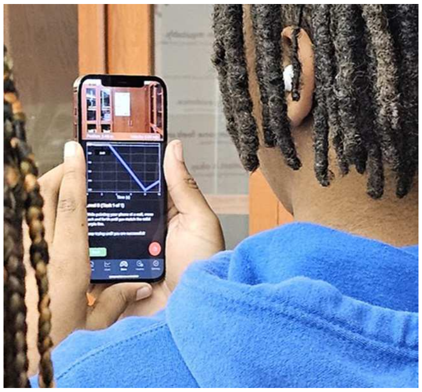


TABLE 2

Questions for reflection.

- What information on the graph tells you about direction and speed?
- What is the meaning of the y-intercept of the graph?
- How can you tell on a graph if you need to stay at a constant speed, speed up, or slow down?
- What did you have to do differently to produce each of the graphs?

Students in the two northeast region classrooms found the app easy to use, and most students completed all tasks. Both teachers indicated that these students typically struggle academically. However, one of the teachers reported that several students who he felt had "tuned out" for the year became highly engaged once they had success with the gamified learning experience. He was impressed with one very persistent student who wanted to achieve all of the challenges on her own (Figure 6). Additionally, her successes demonstrated that the game is accessible to individuals in wheelchairs–a major plus for a lesson that relies on locomotion. These two teachers differed somewhat in how they would use the game in their classrooms in the future: one was satisfied with the lesson flow and would use it again in the same way, and the other would have preferred the option to carry out the tasks in two different class periods, allowing him to focus separately on constant speed versus changing speed. This feedback has contributed to improvements in the lesson.

When our team visited these classrooms, we noted students' enthusiasm and determination to match the graphs and complete the tasks, and observed their improved abilities to characterize motion graphs. We also observed students wrestling with language as they attempted to communicate their ideas about motion, recognizing the importance of linguistic precision when describing motion (e.g., students noted the need to differentiate motion direction, and, hence, the use of terms like displacement and velocity, rather than just distance and speed).

To demonstrate if students could transfer their understanding, they completed a pre-assessment–a modified version of the validated Test of Understanding Graphs in Kinematics (Beichner 1994)–a few days before the lesson and a post-assessment

FIGURE 4

Example student work that shows how graphs can represent different types of motion.

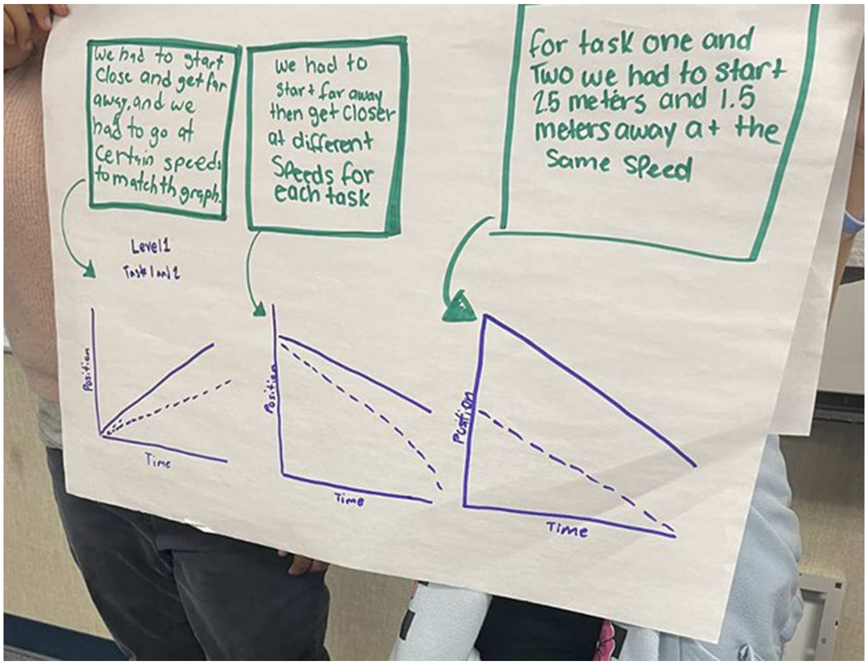


FIGURE 5

One student (left) walks back and forth from a poster board as another (right) serves as a spotter for safety and provides suggestions on how he should walk to match the graph.

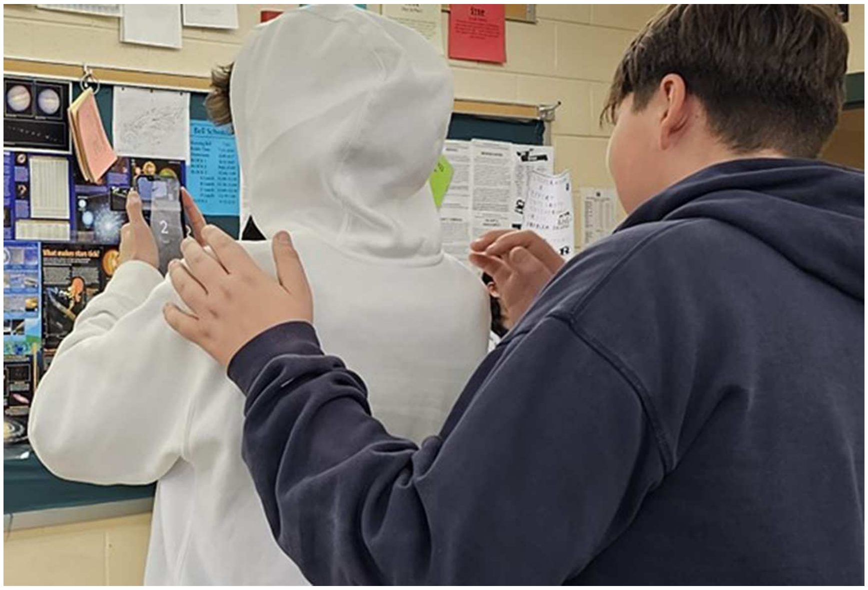
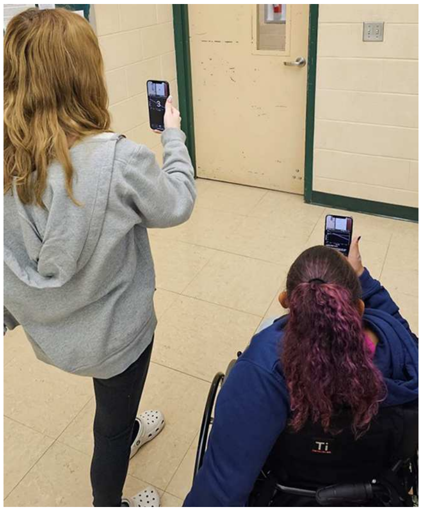


FIGURE 6

Two students work side-by-side on the same motion graph task.



immediately after the lesson. Prior results from testing in an introductory college course revealed significant gains in learning favoring the LiDAR group compared to the sonic ranger group, $t(56) = 4.12$, $p < 0.001$ (Megowan-Romanowicz et al. 2023). The younger students in the 7th grade Southwest class also showed significant within-subject gains from pretest to posttest t ($n = 19$; $p < 0.002$). Meanwhile, Northeastern region students' scores ($n = 11$; revealed more modest (not statistically significant) increases, but this was a small group size. For all these groups, the experience of moving their bodies became a relevant and personalized phenomenon for engaging in deep science practices, setting the stage to work toward relevant performance expectations (see Supplemental Materials).

Using this activity in your classroom

We encourage physical science teachers to make use of the *LiDAR Motion Visualizer* game in their classrooms. We include recommendations to help maximize student success:

- Equipment Availability: LiDAR is currently only available on select iPads and iPhones. However, LiDAR is expected to become more prevalent with future Apple device rollouts. Consider using this opportunity to encourage technology support staff to purchase the "Pro" version of class sets of Apple technology. If permissible and prudent, allow students to bring their own devices, work in small groups, or use a single device as a "station activity" through which students can rotate.
- Dyadic Dialogues: Pair them with partners and have them switch roles of being the holder (holding the iPhone) and one being the helper, the one who gives verbal guidance and makes sure they will not stumble over anything. This increases opportunities for dialogue.
- Personal Safety: Ensure that the walkway against the wall is clear of debris. Use a classmate as a helper or spotter when walking backward away from the wall. Empty corridors outside of a classroom can be ideal for this activity, as long as it does not disturb other classes.
- Device Safety: Include guidelines and policies about technology use in lab contracts, reminding students about the safe handling of devices and the consequences for inappropriate behavior that might result in device damage.
- Scaffolding: Consider having students complete a guided activity sheet (see https://www.lidar-motion.net/lesson-ideas) while completing the tasks. Alternatively, use whiteboard sessions or synthesis notes to help students concretize their learning.

Students who are successful at building intuitive, embodied understandings of motion graphs will be well on their way to understanding Newton's laws and achieving *NGSS* HS-PS-2. These activities may also have added benefits for mathematical thinking, laying the groundwork for advanced topics such as calculus, which often uses motion graphs as phenomena of study. By building this foundation, students can feel confident about their future success in science.

SUPPLEMENTARY MATERIAL

Supplemental data for this article can be accessed online https://doi.org/10.1080/00368555.2024.2404956

ACKNOWLEDGMENTS

Special thanks to Mayra Molinos, Jess Dykes, Tom Pfleger, and the many students who participated in this study.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

FUNDING

This work is funded by NSF Grant #2114586. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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