E D U Q U A K E S

Challenges in Making Meaning from Ground-Motion Visualizations: The Role of Geoscience Knowledge in Interpreting Dynamic Spatiotemporal Patterns

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ABSTRACT

The USArray ground-motion visualization (GMV) is an Incorporated Research Institutions for Seismology (IRIS) video product that illustrates how seismic waves travel away from an earthquake by depicting seismometers as symbols that vary in color according to the recorded amplitudes. GMVs are typically the most popular product the IRIS produces following an earthquake (e.g., $\sim 10,000$ unique views for a recent Oklahoma earthquake). Many instructors feel that dynamic visualizations offer learning advantages over static media when demonstrating dynamic processes, but research indicated they can impede learning by placing greater information processing requirements on the learner. We sought to evaluate changes in student understanding of seismic waves from GMVs by collecting data from three different college-level settings: general student population in a psychology laboratory (novices), students in middle- and upper-level geoscience courses (geoscience majors), and a seismology research group. A seven-question multiple-choice assessment was developed for use in all three settings and then administered in the laboratory and classroom. Using a similar question before and after the GMV viewing, we found that most geoscience majors understood seismic-wave concepts prior to the GMV and the GMV improved their understanding. Only about half of the novices appeared to understand seismic-wave concepts prior to the GMV and performance decreased after the GMV. Performance decreases were larger when students watched an alternative tutorial GMV developed to further illustrate what a GMV represents. An increase in the breadth of incorrect answer selections by novices indicates they became more confused about what happens to energy from an earthquake when shown a GMV. Lower performance on other post-GMV questions by novices suggests that the current style of GMVs are unable to teach basic seismological concepts to people who do not have some formal geoscience training. Although web traffic to GMVs indicates people's interest in watching the videos, watching GMVs does not appear to translate to improved understanding of seismic waves for novices. Future development of dynamic visualizations such as GMVs should consider the cognitive load these learning materials impose on the learner and seek to further implement principles of multimedia instructional design that minimize cognitive processing demands.

Supplemental Content: Multiple-choice quiz focused on assessing basic understanding of the ground-motion visualization (GMV).

INTRODUCTION

Earthquakes generate seismic waves that propagate through the Earth as 3D surfaces, but we typically observe how they interact with the outer surface of the Earth much like we observe ripples on the surface of a pond. Seismometers record the ground motions associated with the passage of numerous seismic waves through a given point near the Earth's surface. For years, the observations were restricted to sparse networks of isolated stations or small aperture arrays. This changed with the Transportable Array component of the USArray/EarthScope project—an array of 400 broadband stations deployed on a uniform 70 km grid that migrated across the United States over a dozen years (Meltzer *et al.*, 1999). Ground-motion data recorded by this very large aperture array, along with those recorded by other stations from contributing seismic networks, have been used for generating visualizations of seismic waves as the energy travels across the United States following large earthquakes.

A well-known example of this is the USArray ground-motion visualization (GMV), a video-based product of the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC; Trabant *et al.*, 2012). This visualization illustrates how seismic waves travel away from an earthquake location by depicting the normalized recorded wave amplitudes at each seismometer location using colored symbols (Fig. 1a; see Data and Resources). The color of each symbol depicts the amplitude of the vertical ground motion, as detected by the station's seismometer and normalized to its

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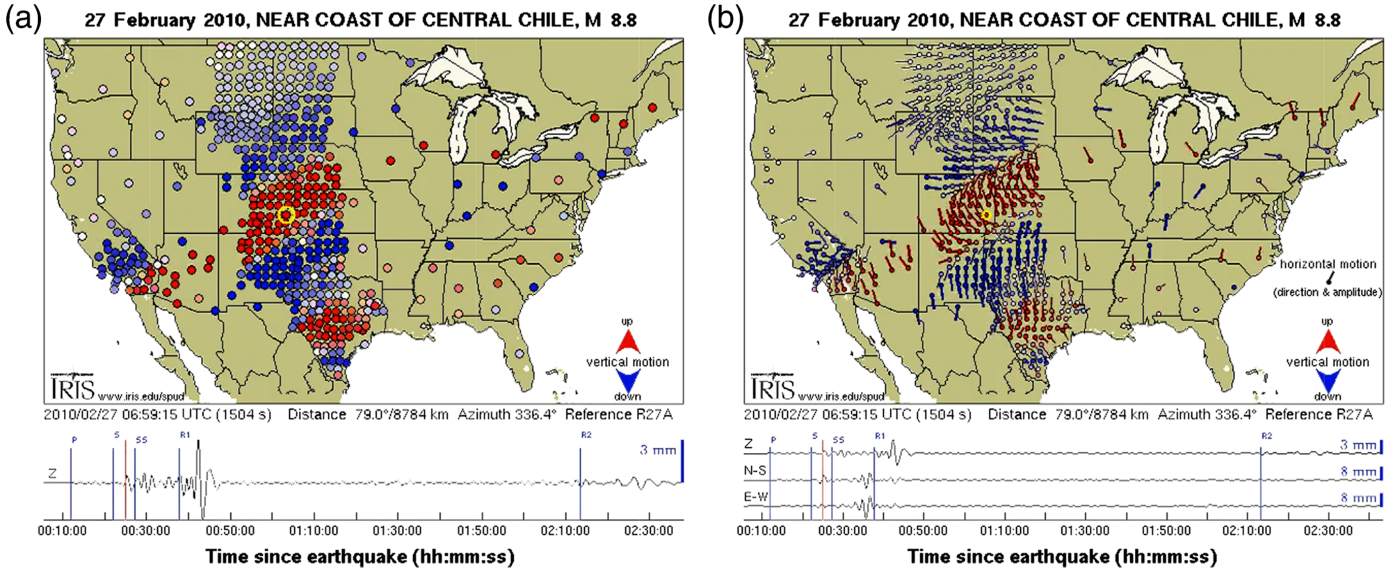


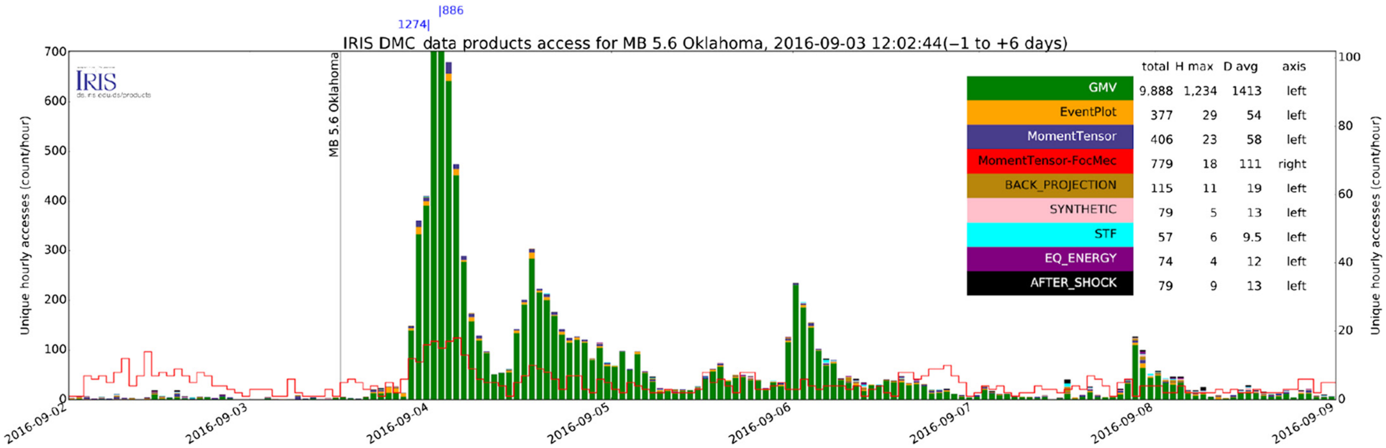
▲ **Figure 1.** Snapshots of (a) the vertical-component ground-motion visualization (GMV) and (b) the three-component GMV for the February 2010 **M** 8.8 Chile event. The color of each symbol depicts the amplitude of the vertical ground motion, and (b) three-component GMVs show the amplitude and direction of horizontal motion by a bar extending from the station location. The color version of this figure is available only in the electronic edition.

peak amplitude. The color changes as waves of differing amplitude travel past the seismometer. Different colors are used to indicate up versus down ground motion with greater saturation of each color indicating larger amplitudes. 3D versions of this visualization have also been compiled to illustrate horizontal motions (Fig. 1b), and there are versions that combine multiple earthquakes from the same source location to create SuperGMVs that illustrate seismic waves rolling across the entire United States (see Data and Resources).

Learning from Dynamic Visualizations

As advances in technology made it possible to produce powerful visualizations of scientific phenomena, the science education research community has begun to investigate the effectiveness of these tools for learning. Intuitively, many instructors feel that complex or dynamic visualizations offer learning advantages over more simplified or static media when teaching about dynamic phenomena and change processes (Ploetzner and Lowe, 2004). Despite the intuitive appeal of this argument, research on learning effectiveness produced mixed results (Bétrancourt and Tversky, 2000; Lowe and Schnotz, 2008; Tversky *et al.*, 2008; Schmidt-Weigand and Scheiter, 2011; Castro-Alonso *et al.*, 2014). In particular, only certain types of dynamic visualizations show an advantage over static visualizations in conceptual learning (Tversky *et al.*, 2002; Höffler and Leutner, 2007). Dynamic visualizations can place greater information processing requirements on the learner (Lowe, 1999). For example, learners may have to process large amounts of information that changes quickly across various regions of the visualization. These requirements can be demanding, overburden learners' cognitive capacities, and impair learning (Ayers and Paas, 2007). Additionally, if visualizations are highly complex or realistic, as many scientific visualizations tend to be, novices may not know where to focus their attentional resources and can be distracted by perceptually salient aspects of the display that are not necessarily task relevant (Lowe, 1999, 2004; Canham and Hegarty, 2010; Hegarty *et al.*, 2010).

Although the effect of dynamic visualizations on learning is still unclear, one reason for their growing use in education is the belief that students find them more interesting and enjoyable and thus, more motivating. In fact, research demonstrated that students do report more enjoyment and motivation for dynamic visualizations compared to static images (Perez and White, 1985; Rieber, 1991). For students to develop a mental model and accurately understand complex scientific concepts, they need to be willing to engage in the cognitive activity required (Schraw, 1998). Many researchers and educators hold the view that increasing interest and motivation in a topic is important for learning and that when a student is more interested or engaged with the learning material, he or she will in turn use more effective learning strategies (Moreno, 2006; Park *et al.*, 2011; Tarchi, 2017). However, the information or images used to make learning materials more interesting or appealing can sometimes lead to poor learning outcomes (Garner *et al.*, 1992; Lehman *et al.*, 2007; Mayer *et al.*, 2008; Jaeger *et al.*, 2018). Further, research on metacognitive monitoring accuracy suggests that interest and enjoyment are not reliable indicators of understanding (Jaeger and Wiley, 2014). Thus, it is important for disciplinary scientists, educators, and science education researchers to collaborate on investigating whether the materials intended to convey information about dynamic phenomena in an appealing manner do in fact support learning.



▲ **Figure 2.** Popularity of publicly available Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC) data products as measured by number of times a product is uniquely accessed per hour. Vertical line marks the 3 September 2016 magnitude 5.6 earthquake in Oklahoma. Image from the IRIS website (see Data and Resources). The color version of this figure is available only in the electronic edition.

The Educational Potential of GMVs

A primary appeal of GMVs is that they are visually enticing and create an opportunity for the audience to feel like they are watching an instant replay of the earthquake. For seismologists, a GMV is likely appealing because it can provide a visual representation of what scientists are utilizing as a mental model. The broader appeal of GMVs is demonstrated by the popularity relative to other products that the IRIS produces following an earthquake. Figure 2 shows the timeline of the IRIS data products accessed by the general public following the 3 September 2016 magnitude 5.6 earthquake in Oklahoma. The GMV generated nearly 10,000 unique views, over 10 times more than any other product the IRIS offers, although most of the other products are intended for scientific analysis and not designed for general public consumption. Other GMVs on YouTube and social media exceeded 100,000 unique views.

Although earthquakes appear to be teachable moments in that they prompt the public to seek information explaining how and why these phenomena occur (Schwarz, 2004; Bravo *et al.*, 2011), there is little research on how effective these moments, and GMVs in particular, are for teaching students the underlying mechanisms involved in the phenomenon. Because large earthquakes are rare in most locations, most people have not experienced a damaging earthquake and would benefit from education about the importance of earthquakes, why and how they occur, and earthquake safety (Southern California Earthquake Center [SCEC], 2003). A key question regarding GMVs is whether they can create improved understanding of seismic waves, because the propagation of seismic energy in the form of waves is what actually causes damage once a fault slips in an earthquake. GMVs seek to represent this rapid dynamic process, which is challenging given that the energy propagates in many different directions and with 3D ground motion, depicted by seismologists as different components of motion (i.e., vertical vs. horizontal). Considering the greater spatial information processing needed to understand this process based on watching a GMV, spatial thinking skills may play a key role in the effectiveness of GMVs.

There is a high demand for spatial thinking skills in the geosciences (e.g., Liben and Titus, 2012), and educational research has begun to directly investigate methods for developing and supporting these skills in students. The Geoscience Education Transdisciplinary Spatial (GET-Spatial) Learning Network is one research group that attempted to tackle these issues. The GET-Spatial project is a collaboration between cognitive psychologists, education researchers, and geoscience educators to develop educational tools that can help students across classroom and field settings to better understand and build upon historically difficult geoscience concepts. As a component of the GET-Spatial agenda, we undertook a study of the effectiveness of GMVs for supporting students' understanding of earthquake concepts. More specifically, considering the public interest in GMVs following an earthquake, we sought to evaluate students' changes in understanding of seismic waves from watching GMVs.

METHOD

Participants

We investigated the impact of GMVs on student learning and understanding of seismic waves across three different settings. The first setting was a controlled study in a psychology laboratory at Temple University. Participants were 45 general population undergraduate students recruited from the Department of Psychology's Research Participation System. All participants completed an informed consent form to assure that the study complied with the ethical standards set forth by the 2010 American Psychological Association regarding the treatment of human participants. Based on self-reporting, very few students had taken a geoscience course, so this group is referred to here as novices.

The second setting was in two classrooms at Miami University, Geohazards and the Solid Earth (majors) and Seismology (upper level). Both courses were taught by the first author. In the majors course, 90% of the students were undergraduate Geology and Environmental Earth Science majors (primarily in their second year of training). In the upper-level course, half of the students were undergraduate Geology and Environmental Earth Science majors, 25% were first-year graduate students, and 25% were undergraduate Physics majors. 41 students from the majors course and five students from the upper-level course agreed to participate in the study.

The third setting was the seismology research group at Miami University, which consisted of two undergraduates and two graduate students. These students only participated in the pilot phase but provided key discussions of what is the critical conceptual information that should be gleaned from GMVs.

Pilot

Prior to conducting the GMV study, pilot data were collected in all three research settings. The purpose of this was to get information about what students thought the video was portraying and what kind of questions students had about the videos. During the pilot phase of the investigation, we employed an open-ended discussion in which we attempted to identify and characterize students' understanding of seismic-wave concepts after watching GMVs. Students were given time (15 min in the psychology laboratory and three days for classroom and research group) to watch a specific GMV (see Data and Resources), and then generate statements about what they thought was occurring and questions they thought of while watching the video. Untimed talk-alouds were used in the laboratory, with participants' attention drawn to different aspects of the displays (e.g., colors, seismogram, and patterns of motion), and then they were asked to explain them using questions in the form of, "I noticed… What do you think is going on…?" For example, participants were asked, "I notice the waves go in different directions and I wonder what is going on. Did you notice this? What do you think is going on when waves go in different directions?" A common response was that the waves were bouncing off each other. Responses were recorded by a graduate student. Students in the classroom and seismology research group wrote their own responses to open-ended questions. We combined the student responses with the instructor-generated alternatives to form a set of seven multiple-choice questions that focused on examining basic understanding of the GMV (see Ⓔ Multiple-Choice Quiz S1, available in the supplemental content to this article).

GMV

Two GMVs were utilized in this study. The first GMV (GMV 1) showed a visualization of real ground motion from the 12 September 2007 magnitude 8.4 Sumatra earthquake recorded in the western United States by EarthScope. GMV 1 has been utilized by the first author in the classroom setting for ~10 yr and includes both vertical and horizontal motion. In the video, vertical motion at each seismometer is indicated by changes in color (Fig. 1) and the direction and size of horizontal motion is represented with small bars. A seismogram at the bottom of the screen shows the vertical ground motion of a single station (C03A) over time. This visualization was created by the IRIS and is ~1.5 min in length. There is no sound or narration, and students were not able to control the speed of the GMV.

Data collected during the pilot indicated that novices struggled to understand the GMV. In response, we developed a second video (GMV 2; see Data and Resources) that utilized a tutorial approach showing GMVs with several different configurations to help illustrate how the symbols represent seismic-wave motions. The tutorial approach was based on a website generated by the IRIS to help a broader audience of people understand GMVs (see Data and Resources). GMV 2 was 4 min and 34 s in length and also included no sound but did include text narration between animation segments. GMV 2 displayed a visualization of real ground motion from a large earthquake that occurred in the Solomon Islands, and another earthquake that occurred in China. The visualization was displayed as a map view that had dots, which represented seismometers in the western United States. GMV 2 not only showed the same map view that was used in GMV 1 but also included three additional vantage points of the earthquakes ground motion: a rotated view, a side view, and a global view. In the rotated view, the map was presented as a side view and illustrated the relationship between the colors and the vertical motion. The side view was shown during the whole frame and was intended to help participants see the patterns of up and down seismic waves, which were moving across the western United States. The global view showed the Earth as a globe starting where the earthquake occurred and then zooming in on the map view. The global view had colored circles, which expanded across the Earth to show how the seismic waves move away from the earthquake in all directions. The global view demonstrated how the waves eventually reached the United States and then shifted the view to this region in the map. Presenting the participants with different views was intended to provide them with multiple representations for visualizing the ground motion of earthquakes over time. Before each view, brief textual explanations were included in the video describing the kind of representation being shown. Participants were allowed to pause the video to read the text, but were not allowed to rewind or change the speed of the video.

Multiple-Choice Assessment

During the experimental phase of the investigation, we utilized seven multiple-choice questions to assess student understanding of the GMVs (see Ⓔ Multiple-Choice Quiz S1). As discussed in the Pilot section, questions and answer options in the assessment were formed from student responses and the classroom instructor's experience with difficulties in student understanding of seismic-wave concepts that can be illustrated by a GMV. Specifically, each of the alternative response options in the test items represented a common misconception that students have about what happens during an earthquake. Question 0 (pre-GMV item) was given prior to watching a

GMV, and all other items were administered after watching the GMV. Question 2 (post-GMV item) was designed to be directly comparable to question 0 to assess whether the GMV improved student understanding of how seismic energy propagates across the Earth's surface. Throughout the article, these two items will be directly compared and referred to as pre-GMV item and post-GMV item.

As with most tests used in a classroom context, the multiple-choice test was explicitly designed for coverage of many different parts of the to-be-learned information, rather than testing for understanding of a single idea multiple times. In general, when Cronbach's alpha has been reported for inference tests, or tests designed for maximal coverage of material, they often have reliabilities in the 0.5–0.6 range (Sanchez and Wiley, 2006, 2010; Griffin *et al.*, 2008). The Cronbach's alpha for the six-item test used in this study was 0.52. Instead of using internal reliability as a basis for evaluation, reliability has been demonstrated through the relation of overall test performance to the pre-GMV item, which showed a significant correlation ($r = 0.22$ and $p < 0.04$) suggesting they were both capturing aspects of student understanding of what happens during an earthquake.

In the lab setting, student responses were collected using Qualtrics survey software and in the classroom setting, responses were collected using the Moodle learning management system. Laboratory participants received one credit for their participation in the study, which is required for course credit in many psychology classes at Temple University. For classroom participants, the multiple-choice questions were deployed as part of a typical daily graded assignment.

Procedure

In the laboratory setting, participants answered a pre-GMV item prior to watching the GMV, and afterward they answered an additional six questions. Students were allowed unlimited time to complete the test, but were not allowed to go back and rewatch the video during testing. Each question was scored as a 1 (correct) or 0 (incorrect), resulting in a total possible score of seven. After completing the multiple-choice test, participants answered a demographic questionnaire that asked them to report their age, gender, year in school, and if they had taken any previous geology courses. The procedure for participants in the GMV 2 condition matched those used in the GMV 1 condition, with the exception that the GMV 2 condition included a modified version of the animation.

In the course settings, the quiz questions were embedded in a regular assignment. This assignment occurred during the meeting of the second class in the first week of the majors course and during the meeting of the ninth class in the fifth week of the upper-level course. Participants answered the quiz questions as part of their regular daily assignments. The questions were delivered, and answers recorded via Moodle. Students were allowed unlimited time to complete the quiz and could rewatch the video, except for the question asked prior to watching the video. The students in the course settings were only shown the GMV 1, not the GMV 2.

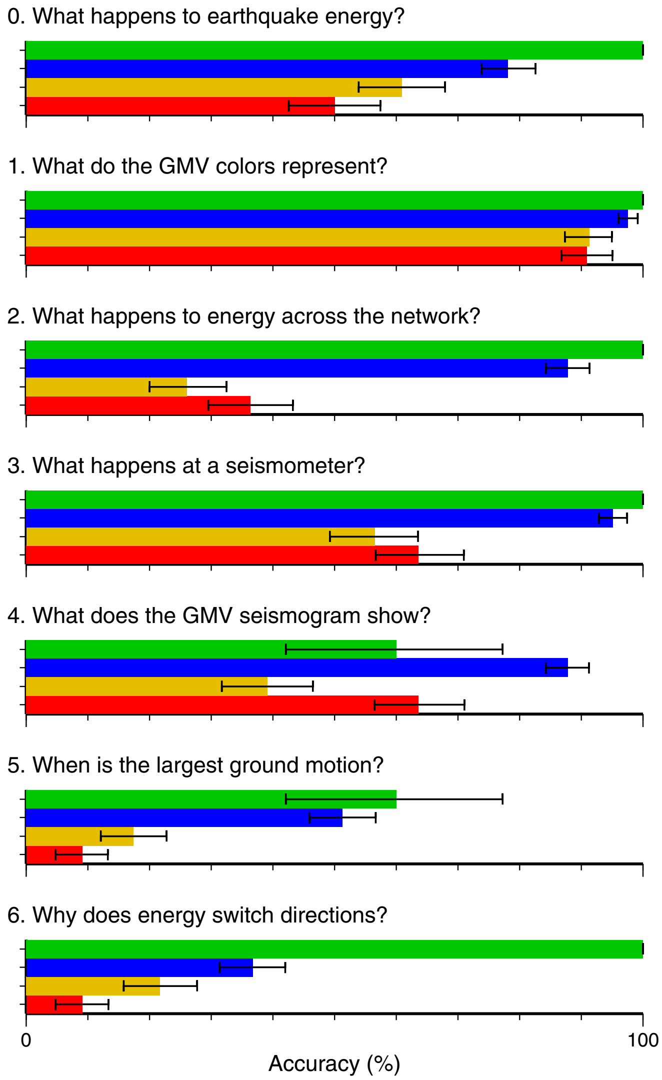
Uncertainty Estimation

For each subset of students evaluated, the average performance was calculated, and 95% confidence interval uncertainties were estimated using a simple jackknife subset resampling algorithm (Kunsch, 1989). For this approach, 10% of the dataset is removed repeatedly and the average performance recalculated 1000 times, taking the second standard deviation of the resulting variability to represent the variance of the measurement. Although the true uncertainty based on variability in the student populations could be higher for our smallest subsets, the calculated uncertainties provide an indication of when the different average values are statistically significant.

RESULTS

Figure 3 shows the percentage of students that chose the correct answer on each of the multiple-choice questions for each of the different student groups. Comparing student performance on the pre-GMV item (Q0) and comparable post-GMV (Q2) item allows us to examine how student understanding of what happens during an earthquake changed after watching the GMV. In the upper-level course, 100% of the students answered the question correctly both before and after watching GMV1, indicating that these students understood basic seismic-wave concepts prior to watching GMV1 and that it did not negatively influence their understanding. In the majors course, accuracy was 78% for the pre-GMV item and 88% for the post-GMV item, suggesting that most second-year geoscience majors understood basic seismic-wave concepts prior to watching GMV1 and that GMV1 positively influenced their understanding. In the laboratory setting, 56% of the students selected the correct answer for the pre-GMV item and only 31% selected the correct answer on the post-GMV item. Because performance went down from 50% to 36% for students watching GMV1, the second tutorial video was developed in an attempt to support understanding. However, after watching GMV2, student performance decreased from 61% to 26%. As indicated by a paired samples t-test, this decrease from the pre-GMV item to the post-GMV item was significant, $t(22) = 2.15$ and $p < 0.05$. These results suggest that only about half of the students who had not taken a geoscience course understood basic seismic-wave concepts prior to watching a GMV, and that watching a GMV negatively influenced their understanding. More specifically, trying to provide additional information about GMVs in the second tutorial video seemed to further confuse students.

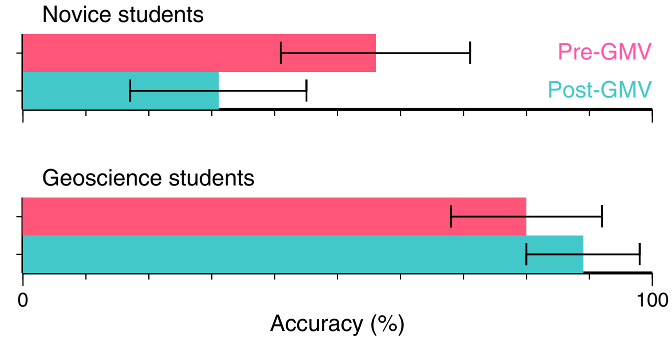
To further investigate differences by knowledge group, data from all lab participants were combined into a single group (novices), and data from all geoscience classes were combined into a single group (geoscience students). Repeated measures analysis of variance were conducted comparing pre- and post-GMV item accuracy as a function of domain knowledge. This analysis revealed a main effect of knowledge group such that the geoscience students (M 0.85) demonstrated overall better performance than the novice students (M 0.43), $F(1, 89) = 55.79$ and $p < 0.001$. Further, there was a



▲ **Figure 3.** Performance on multiple-choice questions by student cohort (bars from top to bottom: upper level course, majors course, lab-video 2, lab-video 1). Brief titles summarize actual question text (see Ⓔ Multiple-Choice Quiz S1, available in the supplemental content). Black bars indicate 2σ uncertainties based on jackknife resampling of the datasets. The color version of this figure is available only in the electronic edition.

significant interaction between pre- and post-GMV item performance and knowledge group, $F(1, 89) = 5.56$ and $p < 0.02$. As shown in Figure 4, follow-up pairwise comparisons indicated that the novice students demonstrated significantly lower performance on the post-GMV assessment item than the pre-GMV assessment item, $t(44) = 2.12$ and $p = .04$.

To better understand these pre/post trends, Table 1 compares the answer choices for the pre-/post-GMV items for geoscience students versus novices. For the geoscience students, only two incorrect answers were chosen prior to the video (cascade of aftershocks and multiple earthquakes), and only two incorrect answers were chosen after the video (vibrate at



▲ **Figure 4.** Pre- and post-GMV assessment item performance as a function of knowledge group. Error bars represent standard error of the mean. The color version of this figure is available only in the electronic edition.

the same time and cascade of aftershocks). The limited number of incorrect selections suggests students were not randomly guessing. Responses to the pre-GMV assessment item indicate that about a quarter of students had a preconceived notion that energy is released via a gradual cascade of aftershocks across the Earth's surface when an earthquake happens. A chi-square test on the pre-GMV responses found the rate of selection was not equal, indicating that students were selecting certain incorrect response options (e.g., cascade of aftershocks) more than others, $\chi^2(4) = 37.81$ and $p < 0.001$. A chi-square test on the post-GMV responses also found the rate of selection was not equal, indicating that students were selecting certain incorrect responses (e.g., an earthquake causes most of the Earth's surface to start vibrating at the same time) more than others, $\chi^2(4) = 54.78$ and $p < 0.001$.

For novices, a similar pattern of response appears to be present on the pre-GMV assessment item, with incorrect responses not equally distributed. Of the 20 students who answered this question incorrectly, 16 selected the cascade of aftershocks answer, which resulted in a significant chi-square test, $\chi^2(4) = 34.20$ and $p < 0.001$. However, novice responses to the post-GMV item showed a different pattern, with incorrect responses relatively equally distributed, suggesting that novices were likely guessing on this item after the GMV, $\chi^2(4) = 4.89$ and $p = 0.30$. Taken together, these results support the notion that novice students with no prior geoscience instruction became significantly more confused about what happens to energy from an earthquake after being shown a GMV, whereas students with a geoscience background did not experience this confusion.

For the remaining five post-GMV multiple-choice questions (Fig. 3), there were no matched prevideo questions to compare with to directly evaluate the influence of the GMV. However, performance on these questions does provide some information on student understanding of the GMV and seismic-wave concepts. For example, students tended to do better on questions related to seismographs than seismic-wave propagation patterns. Independent samples t-tests were run comparing the novices and the geoscience students on each individual

Table 1
Selection Rates for Responses on the Pre-/Post-Ground Motion Visualization (GMV) Items as a Function of Knowledge Group

	Geoscience Pre		Geoscience Post		Novices Pre		Novices Post	
Response Choice	**Number**	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**	**Number**	**Percentage**
R1, cascade of aftershocks*	7	15	2	4	16	36	5	11
R2, earthquake jumps†	0	0	0	0	1	2	8	18
R3, vibrations migrate‡	37	80	41	89	25	56	14	31
R4, multiple earthquakes§	2	4	0	0	3	7	8	18
R5, vibrate at same time⊠	0	0	3	6	0	0	10	22

*R1, the earthquake gradually triggers a cascade of aftershocks across the Earth's surface.
†R2, the earthquake jumps from one place on the Earth's surface to the next over time.
‡R3, an earthquake causes ground vibrations that migrate across the Earth's surface.
§R4, multiple earthquakes send seismic waves across the Earth's surface.
⊠R5, an earthquake causes most of the Earth's surface to start vibrating at the same time and wiggle for a little while.

Table 2
Item Accuracy as a Function of Knowledge Group

	Novices		Geoscience Students		
Question	**Mean**	**SD**	**Mean**	**SD**	***t*-Value**
Q0, When an earthquake happens, what happens to the energy released?	0.56	0.50	0.80	0.40	2.61*
Q1, What do the red and blue colors represent?	0.93	0.25	0.98	0.15	1.04
Q2, What best describes what happens across the whole network of seismometers?	0.31	0.47	0.89	0.32	6.95†
Q3, What best describes what happens at a given seismometer?	0.60	0.50	0.96	0.21	4.50†
Q4, What is the seismogram at the bottom of the animation?	0.51	0.51	0.85	0.36	3.66†
Q5, When does the largest ground motion occur?	0.13	0.34	0.54	0.50	4.53†
Q6, Why does the energy go across the map in one direction and then switch to a different direction?	0.16	0.37	0.43	0.50	3.03*

SD, standard deviation.
*$p < 0.01$.
†$p < 0.001$.

assessment item. As shown in Table 2, the geoscience students scored significantly better on every assessment item except for item number 2 ("What do the red and blue colors represent?"), in which performance was close to ceiling. Novice performance on the other four post-GMV questions was 35%, whereas it was 70% for geoscience students. This suggests that even though the novice students did seem to have some understanding of what the GMV was trying to portray, they were half as likely to use that knowledge to comprehend or interpret the more complex concepts illustrated in the GMV than students with some geoscience training.

INTERPRETATION AND DISCUSSION

Our goal was to directly test the effectiveness of GMVs for supporting student understanding about seismic waves and the spatiotemporal patterns that result after an earthquake. Although GMVs are one of the most highly viewed visualizations provided by the IRIS, and it has been suggested that they support student understanding, no prior research specifically testing this assumption exists. Overall, the present results indicate that students with substantial geoscience knowledge (upper-level course) were best able to understand and interpret the information conveyed in the GMV. Further, students with some geoscience knowledge (majors course) were also able to understand and interpret the GMV, but were not at ceiling-level performance, indicating that even with the GMV, geoscience students may require further instruction to develop full understanding of the phenomenon. Most importantly though, the results demonstrated that students with no prior geoscience knowledge did not benefit from watching the GMV and in fact, novice students showed lower scores on the post-GMV item than the pre-GMV item.

Because the GMV was unsuccessful in supporting novice student understanding of seismic waves and the spatiotemporal patterns following an earthquake event, a second GMV was created in an attempt to provide more support and scaffolding. Despite the intuition that the more detailed and informative video would support novice learning, this was not the case. Performance on most of the test items was either the same or worse for novice students who saw GMV 2 as compared to those who saw GMV 1. Taken together, these results suggest that existing approaches to generating GMVs may result in tools that only support the spatiotemporal thinking about seismic waves for those in geoscience disciplines or those with substantial prior knowledge.

Although one could argue that GMVs were originally designed for geoscientists and were not intended for public outreach, the GMVs created by the IRIS following large earthquakes receive a very high volume of hit counts for views, indicating that a broad audience is interested in these visualizations. However, the present results are problematic for the geoscience community because they suggest that these resources, despite beliefs that they are helpful for education and outreach, are limited in their direct educational benefits for novices. Although the goal of providing publicly available GMVs of earthquakes is to capitalize on teachable moments related to earthquakes and seismic activity (Brudzinski and Jaeger, 2017), and there are instructor communities that utilize the IRIS teachable moment resources including GMVs, the GMVs may not be contributing meaningful information about seismic waves to novice students or the general public. Rather, the high volume of web traffic may be largely driven by people's interest and enjoyment in watching the rhythmic patterns as opposed to the ability of these videos to provide insight into seismic phenomena.

Going forward, the geoscience community should work toward developing more effective methods for conveying conceptual information about earthquakes and seismic waves to nongeoscientists. Initially, those generating informational videos about geologic phenomena should turn to the cognitive psychology and science education literature for information and guidelines about how to develop visualizations that support conceptual learning. This literature indicated one critical element that should be considered is the amount of cognitive load learning materials imposed on the learner (Sweller, 1994). Cognitive load theory is founded upon the idea that humans have a limited amount of cognitive resources that impose a limit on the amount of information a person can process and posits that if the cognitive load of a learning task exceeds the limit of one's working memory capacity, then learning will be diminished. Mayer (2005) developed the theory of multimedia learning (TML) and laid out several principles of multimedia instructional design that are aimed at minimizing the effects of extraneous processing. Often, when research demonstrates a negative impact of dynamic visualizations on learning those visualizations did not closely adhere to the design principles for multimedia learning.

One important TML principle is the coherence principle, which asserts that extraneous material not directly relevant to understanding the main concepts should be eliminated to reduce the amount of information that must be initially processed, thus leaving more cognitive resources available for integration and coordination of relevant information (e.g., Harp and Mayer, 1998; Moreno and Mayer, 2000; Mayer and Jackson, 2005). Similarly, the redundancy principle asserts that people learn better when repeated or redundant information is removed (Mayer *et al.*, 2001). In the present study, GMV 2 was developed to support novice student understanding by providing more detailed information as well as additional representations and perspectives of the same earthquake. However, the coherence and redundancy principles would suggest that, especially for novices who already struggle to comprehend the initial video, simply adding more information will not lead to better comprehension and in fact can harm comprehension. One suggestion for future GMV research is to present each representation and perspective as a separate video and ask students to reflect on how these videos are related and what new information each adds.

Another important TML principle is the signaling principle, which asserts that highlighting essential material by adding overview sentences, headings, or specific narration that emphasizes main ideas will guide the learner's attention and minimize processing of extraneous material (e.g., Mautone and Mayer, 2001; Coyan *et al.*, 2010). Similarly, the spatial and temporal contiguity principles further suggest that corresponding words and pictures should be presented near each other on the page or screen (spatially contiguous) and simultaneously rather than successively (temporally contiguous; Ginns, 2006). The GMVs used in the present study did not contain any narration that explained what was occurring or otherwise directed attention to important aspects of the video. Although more experienced geoscience students may know or have an idea of what to pay attention to during the GMV, novice students do not and thus need support in focusing their attention to optimal areas of the videos. Taken together, all of the TML principles appear relevant in regard to how GMVs are currently portrayed and suggest strategies for improving them.

In a recent review by Jaeger *et al.* (2017), several suggestions are given for developing more effective geoscience learning materials that consider the role of cognitive load. For example, it is suggested that instructors avoid long uninterrupted lectures, in which an unbroken string of information is presented and rather, incorporate active learning techniques. Active learning is thought to be a better approach to learning than traditional lecturing (Freeman *et al.*, 2014), because it can allow smaller chunks of information to be presented at one time, so as not to overwhelm storage capacity. Further, active learning techniques tend to incorporate short breaks between new material that allow students to self-pace acquisition, and to consolidate and integrate the newly learned concepts. These consolidation breaks help students transfer new information into long-term memory more effectively. In the context of instructional settings that use GMVs, future research should investigate the impact of stopping the videos at specific places and asking viewers to reflect on what they have seen so far. This type of intervention could allow students with less prior knowledge or cognitive capacity to take time to digest new concepts and consolidate newly acquired information.

Learning in geoscience can be difficult especially for students because it requires thinking about a complex 3D world that has changed dramatically over time. In the learning process, students interact with many visual and spatial representations (maps, diagrams, models, etc.), which can rely heavily on one's spatial thinking skills (Kastens and Ishikawa, 2006; Liben and Titus, 2012). The GMV used in the present study may have been difficult especially for geoscience novices because it required being able to understand multiple abstract spatial representations and then being able to coordinate them with each other. Parts of the GMV required the visualization of processes or movement that was occurring in a space not shown in the GMV (i.e., the other side of the Earth as the seismic waves pass around it) and dramatic changes in scale (1000s of kilometers across a globe vs. a few nanometers of ground vibration). In addition, a lack of understanding of rock elasticity could limit performance on questions in which novices need to think about rock vibrations. Together, these elements of the GMV suggest that there may be a critical role for spatial thinking skills in being able to accurately interpret GMVs and that if we want students of all ability levels to be able to use these tools, they should be presented in a way that does not require unsupported mental visualization.

Beyond the limitations of the GMV used in this study, the assessment used to gauge learning had limitations. Specifically, the assessment was designed by the authors for the specific purpose of examining students' understanding of the specific GMV used here. Future research may take our findings and initial interpretations as a foundation to work toward developing an empirically tested assessment for understanding the causes of earthquakes and GMVs generally. Further, the questions in the assessment were aimed at relatively complex concepts about seismic waves and earthquakes. One possible reason that learning gains were not seen for the novice students in the present study is that the assessment may not have captured positive changes in their mental model. For novices with little knowledge of earthquakes or seismic waves, they may not have known that an earthquake on one side of the Earth can generate ground vibrations all the way on the other side of the planet. To a geoscience student, this concept may be basic and already a part of their mental model, but to a novice student this idea may have be learned or reinforced by watching the GMV. However, the assessment used in the present study did not include items that would capture all levels of knowledge.

In sum, dynamic visualizations not only do offer various opportunities for learning but also place specific demands on the students' learning processes. In addition to processing continuously changing information, students need to identify relevant elements of the display to attend to while ignoring irrelevant elements, they need to be able to interpret abstract representations of phenomena that may be novel and/or not perceivable to the human eye, and they need to relate spatially and temporally separated components within the display. Although many students can successfully cope with these demands, others are likely overburdened and, as a consequence, may either only superficially process the presented information or may even develop inaccurate representation of the important concepts. When evaluating the effectiveness of dynamic or complex visualizations on conceptual learning, it is helpful to investigate and consider the conditions for which these visualizations might be appropriate and what kind of stylistic and instructional design choices may support learners of various levels of knowledge.

DATA AND RESOURCES

Student data were collected under Temple University Institutional Review Board (IRB) Protocol Number 23869. Earthquake ground-motion visualization (GMV) is available at https://youtu.be/H7f-11A_uBE. SuperGMVs that illustrate seismic waves rolling across the entire United States are available at http://ds.iris.edu/media/product/usarraygmv-super/files/IRIS_GMV_SGMV_50C.mp4. GMV tutorials are available at the websites youtu.be/dkRur0VjJAY and www.iris.edu/hq/programs/epo/visualizations/tutorial. Figure 2 is available at https://ds.iris.edu/files/stats/dataproducts/shipments/images/event/. All websites were last accessed on April 2019.

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