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Diagrammatic Representational Constraints of Spatial Scale in Earth–Moon System Astronomy Instruction

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Abstract

Given that astronomy heavily relies on visual representations it is especially likely for individuals to assume that instructional materials, such as visual representations of the Earth–Moon system (EMS), would be relatively accurate. However, in our research, we found that images in middle-school textbooks and educational webpages were commonly inaccurate in both: (a) the relative size of the Earth and Moon and (b) the relative distance between the Earth and Moon. More specifically, the students' estimates, textbook images, and web images of the relative *size* of the Moon were too large, and of the relative *distance* were too small. We discuss these findings and provide recommendations to science educators.

1. INTRODUCTION

Astronomy is one of the oldest sciences, but it continues to intrigue and engage people of all ages, as is manifested by a yearly worldwide planetarium attendance that is estimated to be between 90 and 100 million visits (Petersen 2005). Learning about astronomical phenomena typically begins at a young age, even before children enter school, via stargazing and informal science-education experiences. With respect to formal education, national science education standards (AAAS 1993 and NRC 1996) call for students to understand the Earth's place in the Universe, celestial motion, and scale. An important first step for understanding scale is the Earth–Moon system (EMS), as the Moon is the closest celestial body to us and is the only one that human beings have visited. Thus, if people lack an understanding of the distance between the Earth and the Moon, they are missing an important first step for understanding the Universe. Therefore, this paper is focused on representations of the Earth–Moon system and how those translate into students' understanding.

Much of the information pertaining to the Earth–Moon system is conveyed diagrammatically rather than through text. This visual mode of representation has been shown to have the potential to improve learning (e.g., Larkin and Simon 1987 and Mayer 1989 and 1990). Unfortunately, because of the spatial scales involved in astronomical phenomenon, providing students with correctly scaled diagrams can be problematic. This paper will explore the following research question: Do the visual constraints of print and digital media influence the instruction of spatial scale in the EMS?

Compare the correctly scaled diagram of the Earth–Moon system (Figure 1) with the typical diagram presented in middle-school science textbooks (Figure 2) shown below.

One challenge for diagrammatically representing EMS information *to scale* is the limited space allowed for displaying figures in print media such as textbooks. First, a standard sheet of 8.5 in. × 11 in. letter paper, with 1-in. margins, will afford inclusion of a figure only up to 6.5-in. (or 16.5 cm) wide. Second, we need to consider the constraints on the set of basic graphical *marks* (e.g., points, lines, areas, etc.) that can be used in noncomputer-based visual representations (Bertin 1977/1981 and Card and Mackinlay 1997). While there is

Figure 1. The EMS drawn to scale.

some variability, according to one publisher of astronomy textbooks (W. H. Freeman and Co.), the minimum size of a print image that can be reliably perceived as round is 1/32 of an inch (approximately 0.8 mm) (N. Comins, personal communication, July 25, 2011).

There are two key ratios of scale in the Earth–Moon system: (1) *Size*: the Earth's width (diameter) is approximately 4 times larger than that of the Moon and (2) *Distance*: The Moon is approximately 30 Earth diameters away from the Earth. The precise measurements are: (1) *Size-Ratio* (Earth's radius = 6,378 km/Moon's radius = 1,738 km) = 3.67 and (2) *Distance-Ratio* (mean separation distance = 384,400 km/Earth's radius = 6,378 km) = 30.13. These are the values used in all statistical calculations discussed herein.

Applying the lower boundary constraint of the diagrammatic representation of 0.8 mm for the smallest round symbol, this would result in a Moon symbol of 0.8 mm in size and an Earth symbol 3.2 mm in size, separated by 96 mm (3.2 mm × 30 Earth diameters)—all of which fits within the 165 mm width constraint of a standard sheet of paper. There is little "space" to expand the size of the symbols for the Earth and Moon. The upper boundary constraint of the diagrammatic representation of the Moon, given the 165 mm width constraint, is 1.3 mm; correspondingly, Earth = 5.2 mm and Distance = 156 mm. In other words, to accurately represent the Earth and Moon to scale on a *standard* sheet of paper, the Moon needs to be between 0.8 and 1.3 mm in diameter.

1.1. Sources of Information

In addition to direct observations, people can acquire information about astronomy and science from a wide variety of sources. These range from popular culture and electronic media (e.g., Gay, Price, and Searle 2007; Kirby 2003; and Olson and Kutner 2008) to informal and formal education (e.g., Brazell and Espinoza 2009 and Resnick 1987). While it is encouraging that individuals now have access to vast amounts of information, we need to recognize that much of the astronomical information that people encounter can be incomplete or inaccurate. This, in turn, can contribute to a range of astronomy misconceptions (e.g., Zeilik and Morris 2003). For this paper, we examined two prevalent sources of astronomy information: (1) science textbooks and (2) the Web.

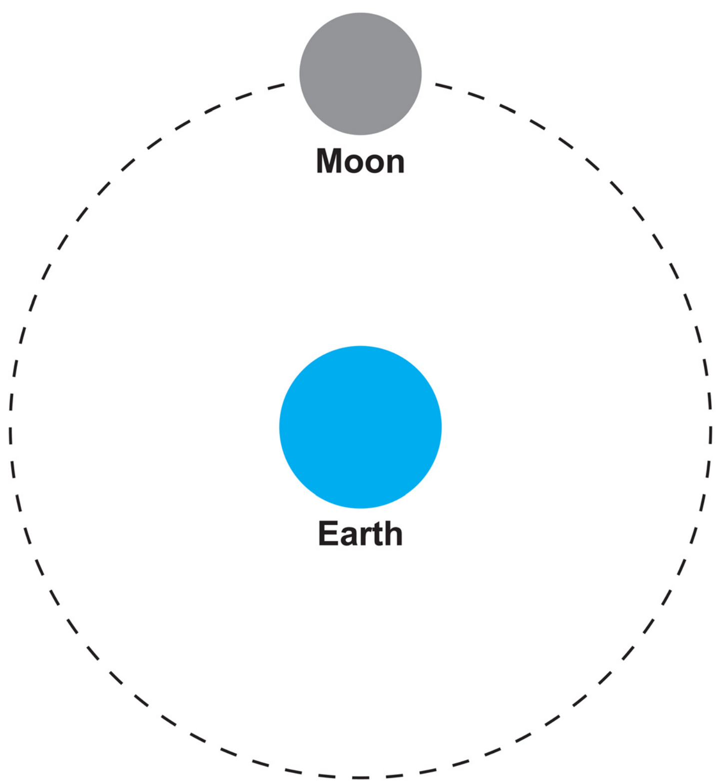

Figure 2. An example of a typical EMS diagram used in middle-school science textbooks.

1.2. Formal Science Education: Textbooks

A major source of students' information about astronomy comes from science textbooks. The 2000 National Survey of Science and Mathematics Education found that textbooks were used in 64% of K-4th grade science classes, 85% of 5th–8th grade science classes, and 96% of 9th–12th grade science classes (HRI 2001). In a separate survey of instructional materials, the National Educational Association (2002) found the following percentages of teacher self-reported textbook usage: everyday = 47%, three or four times a week = 14%, and once or twice a week = 13%.

1.3. Informal Science Education: Web

Another source of information about astronomy is educational material on the Web. Research on how individuals acquire information about science on the web is beyond the scope of this paper. That said, it should be pointed out that in 2008, 54% of the U. S. population reported that the web was their *primary source* of information when examining specific scientific issues (National Science Board 2010).

In summary, our conjecture was that the inherent constraints in diagrammatically representing the EMS would impede accurate representations, with respect to scale, in both formal science education (i.e., textbooks) and informal science education (i.e., Web). This, in turn, we expected to be reflected via an inaccurate understanding of this phenomenon by students.

2. METHOD

This study examined the diagrammatic representations of the EMS produced by 6th grade students, middle-school science textbooks, and science education information retrieved from the web.

The participants in this study were 35 6th-grade students from an urban middle school. All students were individually provided with graph paper and then asked to draw their estimates of the Earth and Moon system to scale.

The *textbook images* consisted of 30 EMS images that were gathered from eight middle—school science textbooks, across four different publishers. The *web images* consisted of 44 EMS images that were gathered from educational or governmental websites. These images were identified though the Google Images search engine, using the search phrases "earth moon" and "moon phases." Criteria for image inclusion were that the Earth and Moon diameters and the distance between the centers of the two objects be clearly observable and precisely measurable. We also noted if any images were labeled as being "not to scale" (NTS).

3. RESULTS

3.1. Size Ratio

As discussed earlier, the correct size ratio of the EMS is approximately 4 (exact = 3.67). In other words, the Earth's diameter is approximately four times as large as that of the Moon. The data in this study were highly skewed, so a one-sample Wilcoxon signed rank test was used as a nonparametric alternative to the one-sample t-test. This statistical test was used to evaluate the EMS size-ratio accuracy of (a) students' estimates, (b) textbook images, and (c) web images. The data and statistical results are described in the text below and in Table 1 and Figure 3.

3.1.1. Student Estimates

The analysis of 35 students' estimated EMS size ratios revealed that their estimates (*Median* = 2.02) were significantly below the correct value (3.67), $p < 0.001$, meaning that students think that the Moon is about two times larger than it actually is.

3.1.2. Textbook Images

The analysis of 30 textbook images revealed that their EMS size ratios (*Median* = 2.67) were significantly lower than the correct value (3.67), $p < 0.001$, meaning that the textbooks depict the Moon is about 1.5 times larger

Table 1. Summary of size ratio results				
	Sample size	**Median**	***p***	**95% CI**
Student estimates	35	2.02	<0.001	(1.74–2.29)
Textbook images	30	2.67	<0.001	(2.67–3.23)
Textbook images (w/o NTS warning)	28	2.90	<0.001	(2.62–3.23)
Web images	44	3.12	<0.01	(2.79–3.53)
Web images (w/o NTS warning)	30	3.03	<0.01	(2.58–3.48)

Note: The correct value for the size ratio is 3.67. NTS: Not to Scale.

than it really is compared to the Earth. Of those 30 images, the same analysis was run on the 28 that lacked "*not to scale*" (NTS) warnings, which revealed that the size ratios (*Median* = 2.90) were still significantly below the correct value (3.67), $p < 0.001$.

3.1.3. Web Images

The analysis of 44 web images revealed that their EMS size ratios (*Median* = 3.12) were significantly lower than the correct value (3.67), $p < 0.01$, meaning that the web images depict the Moon as larger than it actually is compared to the Earth. Of those 44 web images, the same analysis was run on the 30 that did not have NTS warnings, which revealed that the size ratios (*Median* = 3.03) were still significantly below the correct value (3.67), $p < 0.01$. We found that there were seven web images that had the sizes of the Earth and the Moon to be nearly equal, and there were three images that had the size of the Moon six to 12 times smaller than the size of the Earth. It is interesting to note that while we found the web to have an average size ratio closer to the accurate scale, we also found the web images to have more extreme outliers. (See Figure 3.)

In general, we found that the student, textbook, and web size ratios were significantly lower than the correct value. In addition, the removal of the NTS textbook and web images did not significantly change these results.

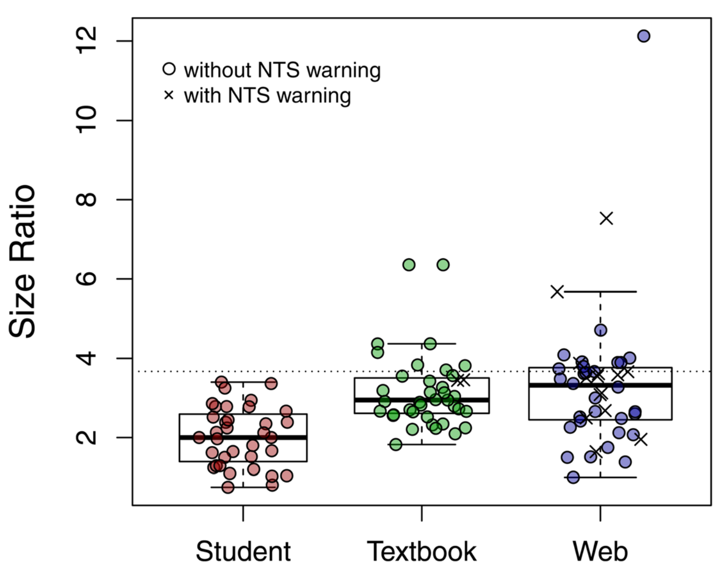

Figure 3. EMS size ratio comparison in the boxplot format: For each box, the thick horizontal line shows the median value and the boxes show the upper and the lower quartiles. The dashed bars show the minimum and the maximum values of the sample, and anything outside of those lines is considered an outlier. The symbols show which data points have warnings about "not to scale" diagrams. The horizontal dotted line indicates the correct size ratio of 3.67.

Table 2. Summary of distance ratio results

	Sample size	Median	*p*	95% CI
Student estimates	35	1.86	<0.001	(1.69–2.05)
Textbook images	30	1.31	<0.001	(1.14–1.47)
Textbook images (w/o NTS warning)	28	1.34	<0.001	(1.16–1.51)
Web images	44	2.09	<0.001	(1.72–2.82)
Web images (w/o NTS warning)	30	1.93	<0.001	(1.57–2.59)

Note: The correct value for the distance ratio is 30.13. NTS: Not to Scale.

3.2. Distance Ratio

As discussed earlier, the correct distance ratio of the EMS is approximately 30 (exact = 30.13). In other words, the distance from the Earth to the Moon is approximately 30 times the diameter of the Earth. The data in this study were highly skewed, so a one-sample Wilcoxon signed rank test was used as a nonparametric alternative to the one-sample *t*-test. This statistical test was used to evaluate the EMS distance ratio accuracy of (a) students' estimates, (b) textbook images, and (c) web images. The data and statistical results are described in the text below and in Table 2 and Figure 5.

3.2.1. Student Estimates

The analysis of 35 students' estimated EMS distance ratio revealed that their estimates (*Median* = 1.86) were significantly below the correct value (30.13), $p < 0.001$, meaning that students think that the Moon is about 16 times closer than it actually is.

3.2.2. Textbook Images

The analysis of 30 textbook images revealed that their EMS distance ratio (*Median* = 1.31) was significantly lower than the correct value (30.13), $p < 0.001$, meaning that the textbooks depict the Moon as about 23 times closer than it actually is. Of those 30 images, the same analysis was run on the 28 that lacked NTS warnings, which revealed that the distance ratios (*Median* = 1.34) were still significantly below the correct value (30.13), $p < 0.001$.

3.2.3. Web Images

The analysis of 44 web images revealed that their EMS distance ratio (*Median* = 2.09) was significantly lower than the correct value (30.13), $p < 0.001$, meaning that the web images depict the Moon as about 14 times closer than it actually is. Of those 44 web images, the same analysis was run on the 30 that did not have NTS warnings, which revealed that the distance ratios (*Median* = 1.93) were still significantly below the correct value (30.13), $p < 0.001$.

In general, we found that the student, textbook, and web distance ratios were significantly lower than the correct value, often by an order of magnitude. In addition, the removal of the NTS textbook and web images did not significantly change these results. (See Figures 4 and 5.)

Overall, in terms of accuracy in scale for both size and distance ratios, all conditions were significantly inaccurate.

3.3. Comparisons Across Student Estimates and Image Sources

In order to determine the significance of the difference between the three representations (student estimates, textbook images, and web images) we computed a nonparametric Kruskal–Wallis test for the variables of size-ratio and distance-ratio using only the images without NTS warnings.

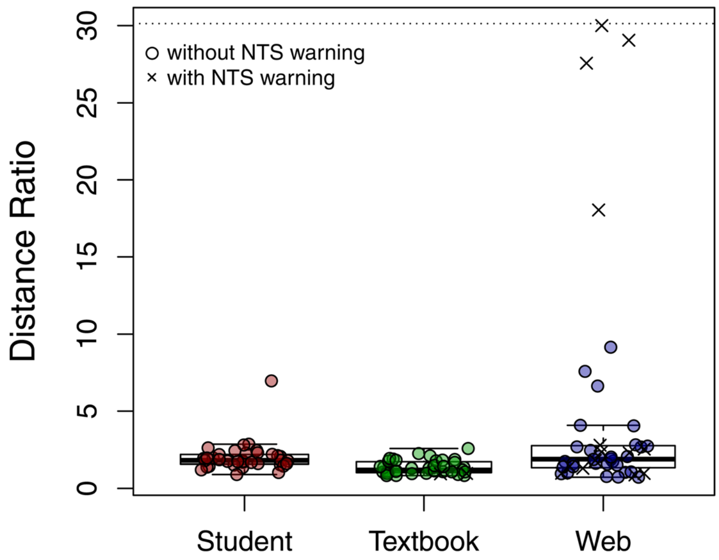

Figure 4. EMS distance ratio comparison in the same boxplot format as Figure 3. The horizontal dotted line indicates the correct distance ratio of 30.13.

3.4. Size Ratio

There was a significant difference in the medians, $\chi^2(2, N = 102) = 25.6$, $p < 0.001$. Follow-up Mann–Whitney U tests revealed that (1) student estimates were significantly less accurate than the textbook images ($z = 4.86$, $p < 0.001$), (2) student estimates were also significantly less accurate than the web images ($z = 3.74$, $p < 0.001$), and (3) textbook images were not significantly different from web images in accuracy ($z = 0.19$ and $p = 0.850$). (See the top portion of Table 3.)

3.5. Distance Ratio

There was a significant difference in the medians, $\chi^2(2, N = 102) = 16.7$, $p < 0.001$. Follow-up Mann–Whitney U tests revealed that (1) student estimates were significantly *more accurate* than the textbook images ($z = 4.14$, $p < 0.001$), (2) student estimates were not significantly less accurate than the web images ($z = 0.05$ $p > 0.05$), and (3) textbook images were significantly less accurate than the web images ($z = 2.71$ and $p = 0.007$). (See the bottom portion of Table 3.)

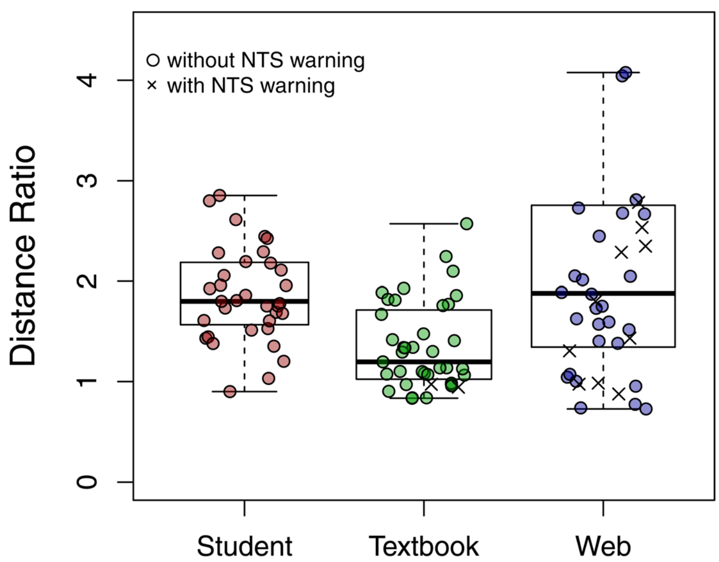

Figure 5. EMS distance ratio comparison zoomed in on the median scores. Note that the correct ratio of 30.13 is not shown within this axis range.

Table 3. Summary of comparisons of student estimates, textbook images, and web images in terms of accuracy of size and distance ratios (excluding images marked as "not to scale")

Dimension	Comparison	Accuracy	Follow-up test
Size	Student versus textbook	Students < textbooks	$z = 4.86$, $p < 0.001$
	Student versus web	Students < web	$z = 3.74$, $p < 0.001$
	Textbook versus web	No significant difference	$z = 0.19$, $p = 0.850$
Distance	Student versus textbook	Students > textbooks	$z = 4.14$, $p < 0.001$
	Student versus web	No significant difference	$z = 0.05$, $p > 0.05$
	Textbook versus web	Textbooks < web	$z = 2.71$, $p = 0.007$

4. DISCUSSION

Returning to the research question motivating this study, we believe that the empirical evidence presented above provides support for the claim that the spatial constraints of diagrammatic representation of the EMS influence science instruction of this phenomenon. Given the inherent challenges of accurately presenting EMS in scale diagrammatically, it is perhaps not surprising that there is still room for improvement in the manner in which this information is presented to students. While additional research is needed in this area, we believe that we can provide some initial guidance to science educators and publishers. Namely, whenever possible, include an accurate visual representation of the Earth–Moon system (e.g., such as that shown in Figure 1). When such representations are not useful/feasible, include an embedded (i.e., annotation *within* the image) NTS warning with figure caption text indicating the correct size and the distance ratios. This embedded warning is especially important for web images as we found several instances where webpage authors would borrow an image from another site but would not include scale information from the original website's caption.

A major limitation of this study is the reliance on students' drawings as the sole measure of their understanding. It is possible that students might have accurate internal (mental) representations of EMS but were unable to accurately translate them into an external diagrammatic representation. We are conducting additional research to investigate this possibility.

In addition, our ongoing research is building upon this work and is seeking to improve instruction on this topic by exploring alternative ways to more effectively present EMS information in both formal and informal learning environments. One specific intervention that we are studying is the use of diagrams that contain multiple levels of magnification (i.e., "zoom boxes"), and how these interact with students' inscriptional practices. A second intervention involves the use of three-dimensional kinesthetic modeling of planetary bodies. We hope that this line of research helps to inform instructional practices in astronomy and science education in general.

REFERENCES

American Association for the Advancement of Science [AAAS], 1993, *Benchmarks for Science Literacy*, New York: Oxford University Press.

Bertin, J. 1977/1981, *Graphics and Graphic Information-Processing*, Berlin: Walter de Gruyter.

Brazell, B. D., and Espinoza, S. 2009, "Meta-Analysis of Planetarium Efficacy Research," *Astronomy Education Review*, 8, 010108, retrieved November 12, 2010.

Card, S. K., and Mackinlay, J. 1997, "The Structure of Information Visualization Design Space." *Proceedings of the IEEE Symposium on Information Visualization (InfoVis)*, infovis, p. 92.

Gay, P. L., Price, A., and Searle, T. 2007, "Astronomy Podcasting: A Low-Cost Tool for Affecting Attitudes in Diverse Audiences," *Astronomy Education Review*, 5, 36.

Horizon Research, Inc. [HRI] 2001. "Report of the 2000 National Survey of Science and Mathematics Education," retrieved July 23, 2008 from http://2000survey.horizon-research.com/reports/status/complete.pdf.

Kirby, D. A. 2003, “Scientists on the Set: Science Consultants and the Communication of Science in Visual Fiction,” *Public Understanding of Science*, 12, 261.

Larkin, J. H., and Simon, H. A. 1987, “Why a Diagram is (sometimes) Worth Ten Thousand Words,” *Cognitive Science*, 11, 65.

Mayer, R. E. 1989, “Systematic Thinking Fostered by Illustration in Scientific Text,” *Journal of Educational Psychology*, 81, 240.

Mayer, R. E. 1990, “When is an Illustration Worth Ten Thousand Words?,” *Journal of Educational Psychology*, 82, 715.

National Education Association [NEA] 2002. “2002 Instructional Materials Survey,” retrieved June 14, 2008 from http://www.publishers.org/school/pdf/2002%20Instructional%20Materials%20report.pdf

National Science Board [NSB] 2010, *Science and Engineering Indicators 2010*, Arlington, Virginia: National Science Foundation.

National Research Council [NRC] 1996, *National Science Education Standards*, Washington, D. C.: National Academy Press.

Olson, C. K., and Kutner, L. A. 2008, “Using Electronic Media to Educate the Public About Science: Coping With the Evolving Media Landscape,” *Media Psychology Review*, 1, retrieved November 18, 2010 from http://mprcenter.org/mpr/index.php?option=com_content&view=article&id=183&Itemid=114.

Petersen, C. C. 2005, “The Unique Role of the Planetarium/Science Centre in Science Communication,” in *Proceedings of the Communicating Astronomy with the Public Conference*, edited by Robson & L. L. Christensen, Munich, Germany: ESA/Hubble.

Resnick, L. B. 1987, “Learning in School and Out,” *Educational Researcher*, 16, 13.

Zeilik, M., and Morris, V. J. 2003, An Examination of Misconceptions in an Astronomy Course for Science, Mathematics, and Engineering Majors,” *Astronomy Education Review*, 2, 101.

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