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Conceptualizing astronomical scale: Virtual simulations on handheld tablet computers reverse misconceptions

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ABSTRACT

Concepts in fields such as astronomy often invoke scales of space and time that far exceed any that are perceived in daily life. Consequently, learners sometimes develop inappropriate intuitions of scale that in turn impede an understanding of related ideas. We investigate whether exposure to virtual 3D simulations of the solar system advances students' understanding of phenomena for which misconceptions often dominate. Here, high school students used handheld tablet computers (Apple iPad) driven by a pinch-to-zoom display to manipulate virtual representations of the solar system. Learning was gauged using a normed concept inventory of multiple choice questions that offered common misconceptions among the answer options. The experiment compared two conditions. One used a simulation where scale relationships in the solar system were exaggerated, so as to focus on surface features of the planets (much like the orrery models often used in astronomy instruction), while the other used a simulation that displayed scale relationships more appropriately. We found that, in either case, even brief exposures to instruction based on pinch-to-zoom simulations of the solar system advanced students' understanding in areas where traditional instruction is notoriously ineffective. Furthermore, displays that used more realistic depictions of scale were more successful in addressing students' misconceptions when scale played an important role in the concept.

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1. Introduction

A quarter century has elapsed since the video "A Private Universe" (Schneps & Sadler, 1987) demonstrated that children and adults hold pervasive nonscientific ideas about commonly observed phenomena, such as the seasons and the phases of the Moon. These ideas have been shown to be remarkably resistant to attempts at instruction (Lightman & Sadler, 1993) and are thought to arise as a natural consequence of knowledge construction (Smith, diSessa, & Roschelle, 1994). The video depicting misconceptions among Harvard students was important because these misconceptions are emblematic of a category of problems in science education that have been the subject of active research in the social construction of scientific ideas (Driver, Asoko, Leach, Scott, & Mortimer, 1994) and the theory of conceptual change (Duit & Treagust, 2003; Posner, Strike, Hewson, & Gertzog, 1982). This work has shown that students perceive their naïve (and often nonscientific) intuitions and ideas as more plausible, sensible, and meaningful than their conception of scientific alternatives presented in instruction (Posner et al., 1982). As a result, well-meaning attempts at instruction may fail to change students' naïve ideas if they do not address the implications of nonscientific ideas previously formed by the learner.

Ironically, concepts in science are prone to a formulation of non-scientific beliefs because learners are able to anchor their understanding on ideas that have rich analogues in daily life, that are nonetheless inappropriate in the context used in science (diSessa, 1985). The notion of scale is an excellent case in point (Swarat, Light, & Park, 2011; Tretter, Jones, Andre, Negishi, & Minogue, 2006). Consider that, for example, early in life learners establish an intuitive understanding that a tiny grain of sand (~1 mm) and a massive boulder (~1 m) can be related to

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one another through scale (of 1:10^3). Such a range in size of three orders of magnitude is easily comprehended through touch and sight. However, while such initiations are useful in many applications drawn from daily life, as science begins to push the boundaries of scale over much larger orders of magnitude, intuitions drawn from daily life no longer suffice. Students often have difficulty conceiving enormous scales occurring in astronomy (Miller & Brewer, 2010). When comparing the size of an electron to the diameter of a galaxy, for example, an analogy between a grain of sand and a boulder does little to capture the enormity of this idea (a scale of 1:10^{33}), and intuitions built from experience that are accessible in daily life can lead learners astray.

Science is replete with concepts that hinge on inconceivably large comparisons of scale involving phenomena such as mass, volume, distance, time, and speed. These occur in the study of geologic time, size and age of the universe, the timeframe of biological mutation and evolution, the mass, size, and speed of subatomic, atomic, and molecular particles, and so on, all examples of important scientific ideas capable of being misperceived when conceptual understanding rests solely on contexts drawn from daily life. This is particularly true for astronomy (Miller & Brewer, 2010), and a number of well-known misconceptions can be traced to inaccurate conceptions about the scales of space (Lightman & Sadler, 1993; Miller & Brewer, 2010; Trumper, 2001, 2006). Among the ideas best studied are those pertaining to the solar system: the size, shape, and gravitational pull of the Earth (Nussbaum, 1979; Schoon, 1992; Vosniadou & Brewer, 1992), distances in the solar system (Dahsah & Phonphok, 2012; Miller & Brewer, 2010), the orbit and geometry of the Earth-Sun-Moon system (Baxter, 1989; Jones, Lynch, & Reesink, 1987), and the cause of the seasons and the phases of the Moon (Cabe Trundle, Atwood, & Christopher, 2007; Fanetti, 2001; Stahly, Krockover, & Shepardson, 1999; Trumper, 2001). A number of instructional approaches have been devised to target these concepts and their associated naïve conceptions (Abell, George, & Martini, 2002; Barnett & Morran, 2002; Bell & Trundle, 2008; Bulunuz & Jarrett, 2010; Cabe Trundle, Atwood, Christopher, & Sackes, 2009; Frede, 2008; Hsu, Wu, & Hwang, 2008; Lindell, 2008, 2001; Prather, Rudolph, Brissenden, & Schlingman, 2009; Sherrod & Wilhelm, 2009; Sneider, Bar, & Kavanagh, 2011; Stahly et al., 1999; Taylor, Barker, & Jones, 2003; Trumper, 2006; Trundle, Atwood, & Christopher, 2007). These generally have met with varying degrees of success, and certain of these ideas (such as the seasons) continue to present challenges (Hsu et al., 2008; Trumper, 2006).

1.1. Using computer simulations to build intuitions of scale

Concepts of scale can be thought about, described, and used in the solution to problems in a number of different ways. One is to compare anchor magnitudes of scale to a linear or logarithmic number line. This approach reduces quantities of distance, speed, time, volume, or mass to a point on a line and then uses visual representation of position on a line as a conceptual anchor for understanding scale. The ability to understand relative proportion in terms of linear relationships is an ability that develops early in life (Lamon, 1996), although abilities to accurately conceptualize these ideas break down as the magnitude of the quantities increase (Ginsburg & Rapoport, 1967; Russell & Ginsburg, 1984). Another strategy for conceptualizing scale is unitizing (Lamon, 1996). Here, scientific scales not easily conceived are related to analogous proportional relationships more meaningful to the learner (e.g., “imagine the Sun as the size of a basketball, then the Earth would be about the size of a pinhead”). This approach has been shown to be effective for conceptualizing scale in both novices and experts (Tretter, Jones, & Minogue, 2006; Tretter, Jones, Andre, et al., 2006), allowing learners to tie abstract notions of scale to concrete concepts that are more easily articulated and enumerated.

In everyday life, people additionally make sense of scale using cues gathered from experience with visuospatial cognition, be they abilities to understand and interpret perspective and depth, or experience of movement and animacy that provide implicit cues about scale (Bobick, 1997; Burgess, Maguire, & O’Keefe, 2002; Tremoulet & Feldman, 2000). For example, experience observing the viscosity of fluids, and its effects on the rate of flow, can provide subtle cues that help a person determine whether a wave is far away and large, or nearby and small. The human visual system is especially well-adapted for extracting inferences about spatial relationships from detail-rich contexts inherent in visual scenes (Brockmole, Castelhano, & Henderson, 2006), allowing a person to learn such relationships implicitly, without being consciously aware of it (Chun & Jiang, 2003). Consequently, many of the intuitions we develop about scale in everyday life are based on experiences and observations that are processed and conceptualized without articulated awareness, via channels for learning that are very different from those often employed when teaching scale in classroom contexts.

That capabilities for implicit visuospatial processing can provide a benefit in learning is demonstrated by recent research linking cognitive enhancements to the use of action video games, an area of study that has gained considerable attention in recent years (Green & Bavelier, 2012; Risenhuber, 2004). Functional magnetic resonance imaging studies have shown that active use of action video games induces plastic changes in neuronal structures that serve to improve the efficiency of visual and visuomotor functionalities (Lee et al., 2012). These changes affect areas linked to early filtering of task-irrelevant information, which is evident as a reduction in activation in fronto-parietal attention networks (Bavelier, Achtman, Mani, & Föcker, 2012; Granek, Gorbet, & Sergio, 2010). Behavioral studies link game use to enhanced visual resolution (Green & Bavelier, 2007), contrast sensitivity (Li, Polat, Makous, & Bavelier, 2009), and temporal discrimination (Donohue, Woldorff, & Mitroff, 2010). They also found changes in abilities for the allocation of attentional resources across space and time (Dye, Green, & Bavelier, 2009; Green & Bavelier, 2003) that lead to enhanced sensitivity to attended detail (Sungur & Boduroglu, 2012) and improved suppression of unattended stimuli (Krishnan, Kang, Sperling, & Srinivasan, 2013). Among other benefits, use of action video games (remarkably, after only 10 hours of play) virtually eliminates gender differences in abilities for mental rotation, a skill especially important in learning geometric relationships in astronomy (Feng, Spence, & Pratt, 2007).

Evidence of cognitive enhancements linked to video game use raises the possibility that 3D virtual modeling may be especially productive in teaching ideas such as the spatial and temporal relationships of planetary bodies in space, including concepts of scale. Virtual 3D computational models have the advantage that they can potentially build on visuospatial capabilities rarely used in education (Mathewson, 1999) to overcome known limitations of static representations and/or physically constructed models (Dahsah & Phonphok, 2012). Computer models can also facilitate use of guided inquiry, in part, by allowing students to test hypothetical scenarios difficult or impossible to realize otherwise (Barab, Hay, Barnett, & Keating, 2000). Researchers have investigated an application of virtual 3D modeling to integrative constructivist learning environments in astronomy, which encourages students to compare their understanding against data provided by the model (Barab et al., 2000; Barab, Hay, Barnett, & Squire, 2001; Bell & Trundle, 2008; Hansen, Barnett, MaKinster, & Keating, 2004a; Moher, 2006). Such studies demonstrate that students who used 3D computational models to construct scenarios testing their understanding were able to develop more sophisticated understandings of the dynamics and spatial geometry of the solar system. These students

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