An Enhanced Framework for Scale Cognition Leveraging Visual Metaphor Theory and Analogical Reasoning Theory

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Abstract: Frameworks for size and scale cognition are synthesized, then enhanced by theory on visual metaphor and analogical reasoning. Future directions developing scale worlds in virtual reality are presented.

Introduction

Cutting-edge science is conducted at extremes of scale, e.g., nanotechnology. Scale is critical in science education too. USA science standards posit scale as a *crosscutting concept* (NRC, 2012). However, students have difficulty comprehending (Tretter et al., 2006a, 2006b) and representing (Delgado & Lucero, 2015) scale, and hold inaccurate ideas about the size of scientific entities (e.g., Delgado, 2009). This paper synthesizes frameworks for scale cognition from STEM education, and enhances these with theory on metaphor and analogy in visual design. The resulting framework can guide research into and development of learning environments for scale.

Background

STEM education research by Tretter et al. (2006a,b) examined conceptual boundaries of scale conceptions and the accuracy of estimation of size of objects/distances. They focused on groups of learners and did not examine individuals' thinking. Delgado (2009) introduced a framework for ways of thinking about scale, influenced by Piaget (e.g., Inhelder & Piaget, 1969), with two qualitative (ordering, grouping) and two quantitative types (relative, absolute size). Magana et al. (2012) added logical proportional reasoning (LPR): using similarity between one ratio of sizes (A:B) and another (C:D), i.e., A:B::C:D (A is to B as C is to D). Kong et al. (2011) developed similar categories starting from nanoscale engineering students' ideas, but with subtypes for ordering and grouping, plus nanoscale-specific "definition" (being able to define nanometer and nanoscale).

Metaphors are foundational tools for learning about the world. In metaphor, aspects of a familiar *source concept* are conceptually mapped onto a less familiar *target* (Lakoff & Johnson, 1980). Conceptual metaphors have an experiential and embodied foundation (Johnson, 1987; Gattis, 2004). Phillips and McQuarrie (2004) identified three structures found in *visual* metaphor: juxtaposition, fusion, and replacement. Placing a car next to a jet (juxtaposition) relates the *target* car to the *source* jet, which has the attributes of being *well-engineered* and *fast*. Visual metaphors have conceptual power, and are linked to attention, elaboration, pleasure, and liking (Phillips, 2003). Peterson (in press) has further developed theory on visual metaphor. Peterson et al. (2015) demonstrated how visual metaphor can elucidate the abstract phenomenon of heat transfer. Visual metaphor theory is relevant for scale cognition because LPR (A:B::C:D) is a type of metaphor.

Analogy conveys that two otherwise distinct situations or domains share relational structure (Gentner & Markman, 1997). For instance, a roughly thousand-fold difference in size (a relational structure) is present in each of the following A:B pairs, despite including diverse, non-overlapping objects: height of human to ant; diameter of EPCOT's dome to diameter of a racquetball; diameter of bacterium to thickness of DNA. The literature does not achieve consensus on how analogies and metaphors differ, but this does not impact our synthesis since we deal with *visual* expressions, where their expressions are roughly equivalent. Metaphor and analogy in general are efficacious in science education (Christidou et al., 1997; Gentner & Wolff, 2000).

Synthesizing scale cognition and visual interpretation theories

LPR operates on ratios, a specific type of structural relationship. The size relationship between ant and human (~1000x) is familiar and thus it can serve as the *source* in a metaphor, to better understand the relationship of bacterium to DNA, a potential *target*. Examples of visual metaphor include *nesting*, where one source–target mapping is then treated as a unit and jointly mapped onto another target. The development of conceptual knowledge in conceptual metaphor theory also involves nesting. Connecting ratios through the use of a common element might be particularly meaningful and powerful for learners. Tretter et al. (2006b) found that scientists construct for themselves *scale worlds* including their everyday, human-scale world and a scale world for their scientific research (e.g., a *nanoscale world*). And yet, scientists felt the need to retain a *connection* among the various worlds. The implication for LPR is that chained ratios with a common element – *nested* LPR (NLPR) – might be more powerful for learning: instead of directly linking A:B::C:D, which lacks a common element, an

A:B::*B*:C::*C*:D chain features connections throughout. E.g., human-to-ant size ratio is similar to ant-to-bacterium, which in turn is similar to bacterium-to-DNA. This sharing of an element across ratios in an analogy is called *cross-mapping* (Gentner & Markman, 1997), and has been seen as a mere coincidence and possible distraction (Yuan, Uttal, & Gentner, 2017); however, we speculate that it might instead be a leverage point for understanding scale, if pairs are *systematically* connected to one another.

NLPR raises intriguing possibilities for mediated instruction in size and scale. Virtual reality (VR) holds great potential for scale cognition because it can provide new *direct* experiences. The familiar is used as source in metaphor, and VR can familiarize learners with entities that are otherwise impossible to directly experience. We envision converting the logarithmic scale into a set of virtual rooms populated by scientific entities at corresponding scales. A student's avatar can stand next to (juxtaposition) or become (fusion) a VR ant, and look at an enormous human, or a minuscule bacterium (now directly visible and manipulable). Additional sensory cues can be incorporated, e.g., using grayscale at sizes smaller than the wavelength of visible light for representations and environments, haptic feedback to represent vibration at the nanoscale, or dramatic echoes for large spaces. An expanded framework for scale cognition represents an opportunity to improve STEM education, with learners' own experiences generating new conceptual knowledge.

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