Unified vs. Tailored Analogies: Effects on Conceptual Knowledge Acquisition

Valerie J. Shute
Armstrong Lab/HRTI
1880 Carswell Avenue
Lackland AFB, TX 78236-5507
(210) 671-2734
vshute@colab.brooks.af.mil

Richard Catrambone
School of Psychology
Georgia Institute of Technology
Atlanta, GA 30332-0170
(404) 894-2682
rc7@prism.gatech.edu

Theoretical Motivation

You have to learn to walk before you can run. Or do you? This simple metaphor for acquiring new knowledge and skills has been implemented in countless pedagogies, but may not be completely true. For instance, in ACT-R [Anderson, 1993] all knowledge starts in declarative form and productions (for carrying out procedures) are formed through an analogy process. Likewise, in SMART [Shute, 1995], the underlying learning theory posits a uni-directional link from symbolic knowledge (SK) acquisition (i.e., knowing basic, abstract curriculum elements[1]), to procedural skill (PS) acquisition (i.e., the application of that knowledge). Conceptual knowledge (CK) is the deeper-level understanding about relationships among SK items as well as the rationale for choosing among different procedures (i.e., the "why" of the material).

An important learning issue concerns ways to facilitate the acquisition of conceptual knowledge. Concepts serve many psychological functions and provide the basis for generalization and other forms of inference. As such, these complex structures contribute to explanations, enabling inferences and deductions about events and ideas [Shute, 1994; Thagard, 1992]. There is growing support in the literature for the notion that analogies, if created and employed properly, can be used to explicitly instruct CK [e.g., Gentner & Gentner, 1983; Glynn, 1991]. For instance, Glynn [1991] has developed a "teaching with analogies" model that provides guidelines for the effective employment of analogies to enhance CK. This model consists of specific operations that one should apply when using analogies as instructional tools (i.e., introduce target concept, cue retrieval of analog, identify relevant features of target and analog, map similarities, indicate where analogy breaks down, and draw conclusions). The order of the operations can vary, but conceptualizations are enhanced (and misconceptions, minimized) if all are ultimately used. Thus, we wish to examine the degree to which we can generate and effectively utilize analogies within the domain of descriptive statistics to enhance CK acquisition.

A related issue is to examine the efficacy of a *unified* analogy used to illustrate multiple concepts versus multiple analogs, each *tailored* to a particular concept. Is a concept (e.g., central tendency) learned better when a unified analogy is used to illustrate its various facets (e.g., Mean, Median, and Mode) or when separate analogies are used to illustrate those facets? Perhaps fine-tuned analogies for each facet are better than a unified analogy that may do only an adequate job on each facet. Spiro, Feltovich, Coulson, and Anderson [1989] have pointed out a number of dangers in using analogies to help convey knowledge (although their comments may apply more to complex knowledge rather than simpler concepts). One particularly intriguing issue is the suggestion that multiple analogies

[1] A curriculum element, or CE, refers to any unit of instruction. CEs may vary in grain size from low-level bits of knowledge and skill, to more global units, depending on the needs of the particular learner population and the instructional goal(s).

for a single topic have the advantage of helping the learner to overcome mis-mappings and misconceptions induced by the reliance on a single analog. Our project examines a similar notion in that we contrast a single analog versus multiple analogs, but we carry out this contrast across *three* concepts, in which each is illustrated by a unique analog or by the same analog. This contrasts with trying to convey a *single* concept using either a single analog or multiple analogs. The findings of Spiro et al. [1989] have implications for our work; nevertheless, the situation they examined (learning a single, albeit complex, concept with the aid of a single analog versus multiple analogs) is different from ours (learning a few related concepts with the aid of a unified analogy or separate analogs for each concept).

Empirical Motivation

Two controlled evaluation studies have recently been completed that examined Stat Lady learning outcomes as a function of the presence or absence of the student modeling component (SMART) [Shute, 1995]. The specific set of findings that motivated the current research involved a significant 3-way interaction, obtained in both studies: learning gain × outcome type × aptitude level. In general, low-ability learners showed dramatic pretest-posttest improvements for SK and PS, but only moderate gains for CK; high-ability learners improved equally across all outcome types (note: "outcome type" refers to categories of knowledge/skill--SK, PS, CK). This finding inspired the current research to determine some way to similarly boost CK acquisition, especially for low-ability learners. We are conducting an experiment designed to: (a) examine the effects of supplementing conceptual knowledge instruction (about measures of central tendency) with analogies, and (b) investigate the effects of employing a unified analogy versus tailored analogies for that CK instruction. We believe that the introduction of an analogy may ultimately enhance the acquisition and memorability of CK elements and also help learners acquire related PS and SK elements.

Project Description[2]

The criterion task that we're using to test the current hypotheses about analogy effects on learning is one of the Stat Lady Descriptive Statistics (DS) modules that teaches issues of central tendency [Shute, Gawlick & Lefort, 1996]. The program's curriculum was derived from a cognitive task analysis of the domain. Each of the more than 100 curricular elements are instructed and assessed within Stat Lady, then additionally assessed via pre- and posttests to examine changes in learning due to the treatment conditions.

Pedagogy

To illustrate, Stat Lady instructs a particular CE (or small group of related CEs), such as the procedural knowledge associated with determining the Median from a set of numbers. Subsequently, learners are presented a problem set designed to assess their skill and understanding. Learners obtain data from the "Number Factory" and then proceed, step-by-step, to solve the problem that requires them to figure out the Median from their unique set of data. Three-level feedback (i.e., progressively more explicit) is provided by Stat Lady when learners solve the problem or make an error. The system updates its record(s) about whether learners have learned particular CEs and the degree of mastery of that learning.

CE-Derivation and Analogy Construction

As mentioned, we began this project by systematically decomposing the curriculum into a hierarchically-related set of CEs that were subsequently classified into three outcome types. We then created analogies for instructing the higher-level CK elements (in this case, Mean, Median, and Mode). For example, with regard to Stat Lady instruction on the Mean, an on-line seesaw appears with numbers arrayed along the board, similar to the x-axis of a

[2] This paper describes an experiment-in-progress. And while preliminary findings will be presented at the conference, unfortunately, no data are currently available.

graph. Boxes are stacked to different heights above the numbers; the heights representing frequencies. Moreover, the seesaw consists of a moveable fulcrum so that learners can slide the fulcrum, horizontally under the board, until the board (tipping appropriately in relation to the fulcrum) becomes balanced [see Fig. 1]. While the fulcrum is moving, numbers dynamically appear within it representing the corresponding point/value along the board (x-axis). The number that shows up when a balance state is attained reflects the Mean for those particular data.

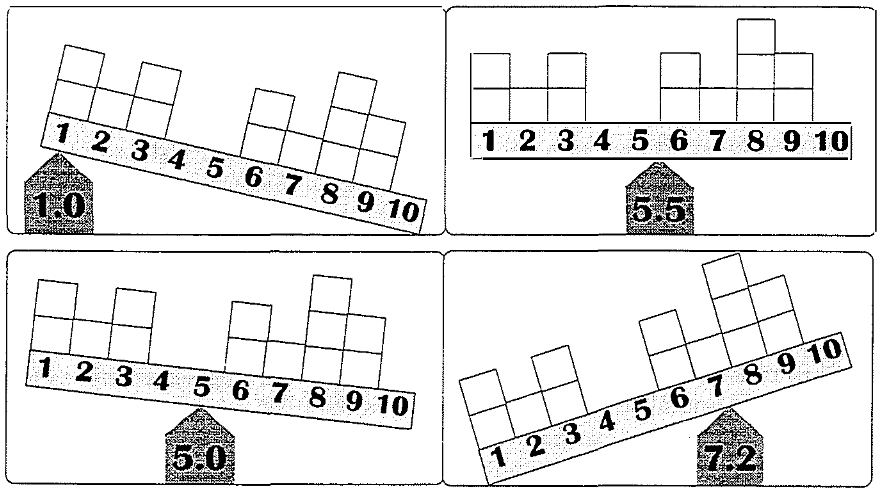

Figure 1: Seesaw Analogy, Illustrating the Mean

CK Instruction via Unified Analogy

The mapping between the seesaw (base domain) and the Mean (target domain) would be as follows: To "balance" a seesaw, one needs to distribute the "weights" such that they occur "equally" on either side of the fulcrum. To achieve this state, either the weights or the fulcrum can be moved around. The weights represent different magnitudes of numbers, and the Mean maps onto the fulcrum when it has reached the balance point [5.5 in Fig. 1]. Learners are given the opportunity to manipulate the seesaw by moving the fulcrum to balance the seesaw for different weight distributions.

The mapping between the seesaw and the Median is less straightforward. The seesaw would become balanced (i.e., horizontal) when the fulcrum is moved to the Median value. In Figure 1 this value would be 6. The mapping between the seesaw and Mode is even less intuitive. In this case the seesaw will balance when the fulcrum is under the tallest pile of boxes [8, in Fig. 1]. This situation could look very odd and violate the expectations of most learners. However, the value of using a unified analogy for instructing the Mean, Median, and Mode may outweigh this potential disadvantage. The mismatch between the physical reality (balancing only at Mean) and the demonstration (balancing at Median and Mode) is precisely the point. That is, when the learner sees the seesaw balancing at the Mean but then later not balancing at the Mean, but rather at the Median or Mode, this may make the distinction among the concepts that much clearer, thus may help the learner understand how the analogy differentially applies (or "breaks down" in Glynn's 1991 framework).

CK Instruction via Tailored Analogies

In contrast to the above argument for the value of a unified analogy to teach related concepts, perhaps analogies that are specially tailored to each facet of a concept would be more useful. Each analog could provide a mapping to the relevant facet that might be more straightforward than the mapping involved in using a unified analogy, thereby improving the degree of conceptual knowledge acquisition.

For instance, Figure 2a represents a "folding paper strip" analog that provides a clear mapping between position on the strip of paper (or number line) and the Median. Figure 2b contains "hanging buckets of balls" that shows a mapping between frequency (number of balls) and how far a bucket descends.

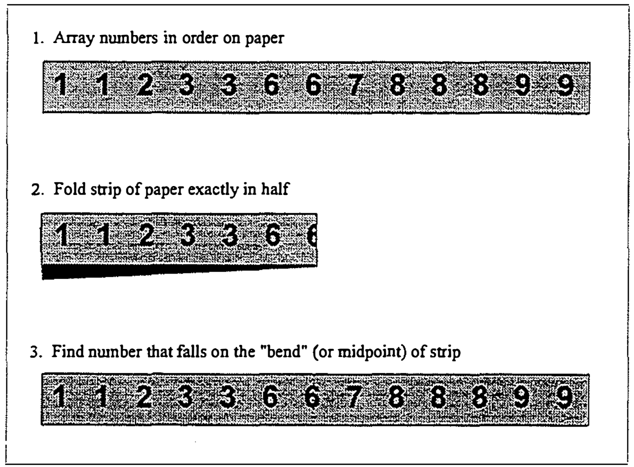

Figure 2a: Folding Paper Strip, Illustrating the Median

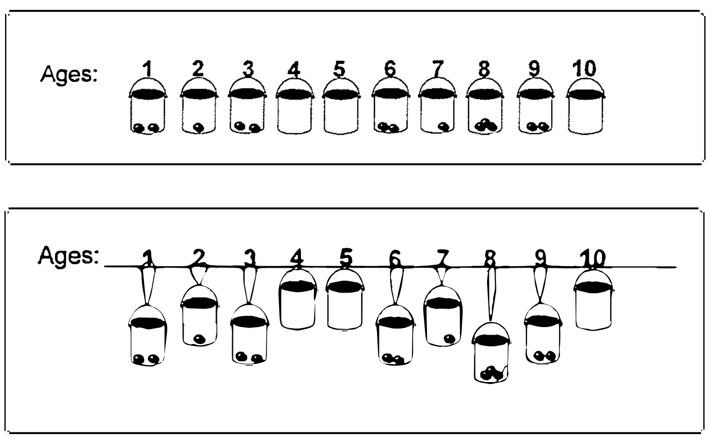

Figure 2b: Hanging Buckets of Balls, Illustrating the Mode

In summary, we are interested in analogy effects on CK acquisition--Is conceptual knowledge acquisition facilitated as a function of using analogies for instruction/remediation in contrast with a condition involving no analogies, and does this ultimately enhance SK and PS acquisition as well?

Experiment

To assess learning, we analyze pretest to posttest changes in performance on a set of matched items, administered on-line (before and after Stat Lady instruction, respectively). Data are analyzed separately per outcome type and by experimental condition (i.e., no analogy, unified, or tailored).

This particular Stat Lady curriculum consists of 130 CEs covering the main topics of central tendency as well as lower-level issues (e.g., computing the Mean from data sets having frequencies > 1, being able to find the Mode from a frequency distribution). Each of the three primary CEs (Mean, Median, Mode) has its own set of "children" as the entire curriculum was decomposed in a top-down manner, resulting in a hierarchy of CEs.

The three treatment conditions for this study are: (a) *No Analogy* (Instruction Only)--presentation of the instructional material without any analogies; (b) *Unified Analogy*--same instruction as the No Analogy condition, but using a unified analogy (i.e., a seesaw with manipulable fulcrum) to supplement the standard CK instruction for the three main concepts of Mean, Median, and Mode; and (c) *Tailored Analogies*--same instruction as the No Analogy condition, but using three different analogies to supplement CK instruction: Mean = Seesaw (like in the Unified Analogy condition), Median = Folding Paper Strip, and Mode = Hanging Buckets of Balls.

Hypotheses and Experimental Tests

Analogy Effect(s) on CK Acquisition. Supplementing conceptual knowledge instruction with analogies may enhance the memorability of CK elements (a *retention* issue), and also facilitate the acquisition of CK and related SK and PS elements (a *learning* issue). Learning outcome and efficiency measures are hypothesized to be positively affected by the use of analogies. To empirically test these issues, we will examine (across various periods of time--immediately and following some lag) the effects of different treatment conditions on learning outcome and efficiency for each outcome type (SK, PS, CK) and include various aptitude measures in the equation.

Analogies vs. No Analogies. The No Analogy condition will be contrasted with the Unified Analogy and Tailored Analogy conditions to test any main effect due to analogies. We will also examine learning gains to see if the impact is equal across outcome types. While we hypothesize that PS should see greater gains (particularly for low-ability learners) due to the presence of analogies, there should also be a significant boost for the CK elements themselves. A related issue is whether analogies aid long term access of CK (and possibly SK and PS). Long term retention issues are beyond the scope of the current study, however.

Unified vs. Tailored Analogies Effect. A straightforward contrast between the unified- and tailored-analogy conditions will demonstrate any main effects attributable to using unified versus tailored analogies to supplement the teaching of conceptual knowledge. We suspect that the tailored analogies will result in better CK outcomes (and possibly PS outcomes as well) given they have been tailored to suit each concept. However, if the unified framework makes the distinction among Mean, Median, and Mode sharper, then learners receiving the unified analogy may actually better remember the procedural differences in calculating those values as well as the conditions under which each facet is most appropriate. That is, a unified analogy may encourage learners to compare and contrast the three measures of central tendency. This is a twist on the argument by Spiro et al. [1989] in which they suggest that multiple analogs can help a learner avoid misconceptions about a single concept; in the present case, the application of a single analog to multiple concepts may also help the learner avoid misconceptions.

Discussion

Analogies appear to help the acquisition and retention of conceptual knowledge (CK). A salient question then concerns the components and attributes of an effective, explanatory analogy. The work of D. Gentner [e.g., Gentner, Rattermann, & Forbus, 1993] suggests that overlap in terms of relations among attributes and relations among relations might provide a useful metric in determining the "soundness" of an analogy such as the soundness of the analogy between a seesaw and the Mean.

In addition to the components of effective analogies, certain processes aid learning and transfer. Efforts to make the mapping, and the functionality of the mapping, between base and target more explicit can help the learner use the analogy more effectively. For instance, Catrambone and Holyoak [1989] found that instructions that led learners to focus on relevant mappings between a base and target during instruction also led them to spontaneously apply the analogy to the target, even after a delay between reading the base and solving the target. Across five experiments they found that transfer is typically enhanced when: (a) multiple examples are used rather than just a single one, (b) explicit, directive comparison instructions are given versus implicit (or no) directive instructions, and (c) more problem-solving experience is provided in contrast to passive observation.

If the base analog is relatively easily understood, then the teacher or tutor must be concerned with making sure the mapping is straightforward, robust, and reliable. One question in the present study is whether the seesaw analogy is the appropriate "unified" analogy to use. That is, perhaps the folding paper strip analogy would be more effective as an overall framework and thus, the results will be different if this analogy is used. Future studies can test this notion by systematically varying which analogy is used as the unified one and which ones are used as the tailored ones for each facet of a concept.

A related concern is the order in which the three main concepts are instructed. Suppose Median, Mean, and Mode is the best order if no analogies were presented. When a unified analogy is used, then there might be an interaction with order and type of analogy such that the concept that is instructed first dictates the unified analogy that is used. For instance, if Mean must be first, and a unified analogy must be used, then the seesaw analogy might be the one to use since it applies fairly cleanly to the Mean and can quickly give the learner a reasonable foundation on which to build the upcoming concepts (Median and Mode). However, if the Median is first instructed, and a unified analogy must be used, then the folding paper strip analogy might be more effective since it maps so well to the Median and allows the learner to build a good foundation. This issue will be examined in future studies.

A third issue for future work is whether the analogies used to aid learning can backfire and make it difficult for the learner to go beyond the analogy and understand the concept successfully [see Spiro et al., 1989]. We can examine this issue to some degree by examining how well learners can transfer their knowledge about the concepts to novel situations such as determining the appropriate situations for using particular central tendency measures. We can do a more intensive investigation of this issue by examining how well learners can acquire knowledge about more complex concepts that use as building blocks simpler concepts that were instructed with the aid of an analogy or analogies.

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