Animation Facilitates Source Understanding and Spontaneous Analogical Transfer

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Abstract

Research on analogical problem solving has found that people often fail to spontaneously notice the relevance of a source analog when solving a target problem, although they are able to form mappings and derive inferences when given a hint to recall the source. To investigate the determinants of spontaneous analogical transfer, the present study systematically compared the effect of augmenting verbal descriptions of the source with animations or static diagrams. Solution rates to Duncker's radiation problem were measured across varying source presentation conditions, and participants' understanding of the relevant source material was assessed. Supplemental animations increased both comprehension of the source analog and spontaneous transfer to the radiation problem. Supplemental diagrams yielded lesser improvement in participants' understanding of source material and did not increase solution rates to the target problem. To investigate individual differences in spontaneous transfer, fluid intelligence was measured for each participant using an abridged version of the Raven's Progressive Matrices (RPM) test. Animated source depictions were most beneficial in facilitating spontaneous transfer for those participants with low scores on the fluid intelligence measure.

Keywords: Analogy; animation; multimedia learning; transfer; intelligence

Introduction

The human ability to make inferences and solve problems involves comprehension of abstract principles that often apply across superficially dissimilar systems. Analogical inference–the application of knowledge about a familiar source system to a novel but structurally similar target system–is critical in scientific discovery (Dunbar & Klahr, 2012) and many other aspects of creative human activity (Gentner, 2010; Holyoak, 2012; Holyoak & Thagard, 1995). The human capacity for abstract thinking, which is exemplified by analogical reasoning, exceeds that of any other species and plays a significant role in formulating ideas that transcend direct perception (Penn, Holyoak & Povinelli, 2008).

Spontaneous Analogical Transfer

It is generally recognized that analogical reasoning involves several subprocesses, most notably retrieval of a related source analog, mapping, inference, and subsequent generalization (e.g., Holyoak, Novick & Melz, 1994). A basic finding is that when a source and target are drawn from different knowledge domains and encountered in different contexts, a potentially useful source analog often remains unnoticed. The gap between noticing and actual use of a source analog has been explored most extensively in experiments using Duncker's (1945) radiation problem as the target analog. In this problem, a doctor must find a way to use a radiation ray of varying intensity to destroy an inoperable stomach tumor in a patient. The essence of the problem is that high-intensity rays will destroy healthy tissue when they pass through it on their way to the tumor. While low-intensity rays do not harm healthy tissue, they are also ineffective in damaging or destroying the tumor. The convergence solution is to apply multiple low-intensity rays to the tumor simultaneously from multiple locations surrounding the target.

Gick and Holyoak (1980, 1983) found that in the absence of a related source analog to draw from, about 10% of the participants were able to generate the convergence solution to the radiation problem. When a verbal story highly dissimilar to the radiation problem (a story about a general using converging troops to capture a fortress) was given to participants prior to the target problem, the rate of spontaneously generating convergence solutions increased to about 30%. After receiving an explicit hint to recall the source analog, approximately an additional 50% of the participants gave the convergence solution, for a total solution rate of roughly 80%. Thus, people often failed to spontaneously notice the relevance of the source in solving the target problem, though they could successfully form mappings and derive inferences when prompted to do so.

Spontaneous transfer can be facilitated in a number of ways–e.g., choosing a source analog that is relatively similar to the target (Keane, 1988), or one that permits a clear, isomorphic mapping to the target problem (Holyoak & Koh, 1987). Close comparison of multiple source analogs appears to aid in abstracting a more general schema for a class of problems, which in turn fosters later spontaneous transfer (Catrambone & Holyoak, 1989; Gick & Holyoak, 1983; Loewenstein, Thompson & Gentner, 2003).

Visuospatial Displays and Analogical Transfer

Research on diagrammatic reasoning has shown that visuospatial representations of solution strategies for mechanical problems can enhance people's ability to infer the principles of operation of physical systems (Hegarty & Stull, 2012), suggesting the importance of display format in acquisition of abstract knowledge. A few studies have shown that static, visual diagrams can be used as source analogs for verbal target problems (Gick, 1985; Gick & Holyoak, 1983). While uninterpreted diagrams generally result in low rates of spontaneous transfer, they can serve as effective analogs following a hint to recall and apply them to a novel target problem (Gick & Holyoak, 1980).

In contrast, there is some evidence that *animated* displays can facilitate spontaneous transfer (Beveridge & Parkins, 1987; Pedone, Hummel & Holyoak, 2001). The radiation problem is temporally dynamic, in that the key concepts involve the summation of forces over space and time. The use of physical motion in an animated display may help the learner to focus attention on dynamic relationships (Tversky & Morrison, 2002), which may in turn provide additional retrieval pathways when the target problem is encountered. Day and Goldstone (2011) found that presenting a force-based physical system can prime dynamic mental models, which in turn facilitates spontaneous transfer when solving problems based on superficially dissimilar dynamic systems.

The present experiment aimed to systematically compare the effectiveness of animations and static diagrams–combined with verbal descriptions–in facilitating spontaneous analogical transfer to the radiation problem. The animations and diagrams tested by Pedone et al. (2001) were presented without any verbal cover story, and no measures of participants' understanding of the source analogs were obtained. There is evidence that the combination of animations and oral narration is especially effective in increasing understanding of a mechanical system (Mayer, 2009; Mayer & Anderson, 1991). Thus, animations may provide deeper insight into the causal structure of a dynamic system than does a verbal description alone. To assess this possibility, the present experiment included measures designed to assess participants' understanding of the source analog. We hypothesized that animations would improve initial understanding of the source and facilitate subsequent spontaneous analogical transfer.

A secondary aim of the present study was to investigate potential individual differences that may predict success in spontaneous transfer. There is a great deal of evidence that measures of fluid intelligence, notably Raven's Progressive Matrices (Raven, 1938), predict performance on standardized analogy tests (Snow, Kyllonen & Marshalek, 1984). However, such tests always present the source and target together (typically in A:B :: C:D format), so that the need for spontaneous retrieval of the source is eliminated. Relatively few studies have examined individual differences in analogical problem solving (Antonietti & Gioletta, 1995; Corkill & Fager, 1995; Novick & Holyoak, 1991). The present experiment is the first to investigate whether fluid intelligence scores predict spontaneous analogical transfer. By measuring individual differences, we were also able to determine whether the impact of animation differs for people at varying levels of fluid intelligence.

Experiment

Participants

A total of 126 participants were recruited from the Department of Psychology subject pool at the University of California, Los Angeles, and were compensated with course credit. Participants were randomly assigned into one of three conditions (Verbal, Verbal + Diagram, and Verbal + Animation), and were naïve to the purpose of the experiment.

Materials and Procedure

An initial instructions page outlined the general elements of the source system, which was comprised of four scenarios presented in sequential order. Participants in each condition received an auditory-verbal (spoken monologue) version of each scenario. Those in the Verbal condition were only presented with the spoken monologue, whereas subjects in the Verbal + Diagram and Verbal + Animation conditions received a supplemental diagram or animation, respectively. Figure 1 illustrates the diagrams used in the experiment. Videos of the animated scenarios, along with their accompanying spoken monologues, are available online at *http://cvl.psych.ucla.edu/moviedemo.html*.

In each of the four scenarios, one or more cannons attempt to defeat an enemy octagon surrounded by a friendly barrier by shooting at it with cannonballs of various sizes. The goal of the cannon(s) in each scenario is to defeat the enemy octagon without allowing any local region of the barrier to exceed a critical level of damage. This successful scenario is analogous to the convergence solution to Duncker's radiation problem, in which multiple radiation sources are fired at low intensity from multiple locations surrounding the patient's stomach, successfully destroying the tumor without inflicting critical damage to any local region of the surrounding healthy tissue. The relational structure of the cannonball scenario is thus isomorphic to the key relations in the potential solution to the radiation problem.

Questions related to each scenario were presented sequentially following the presentation of all four scenarios. Participants answered two multiple-choice questions per scenario, which assessed their understanding of the damage inflicted to the key elements in each system (e.g., "What level of damage did the cannonballs cause to the friendly barrier in Scenario #1?"). The choices given for damage level were (1) none, (2) minor, (3) moderate, and (4) major. Damage level was directly stated in the spoken monologue for each scenario. After completing the multiple-choice questions, participants were asked to explain why the cannon(s) failed or succeeded in meeting the objective in each scenario (one free-

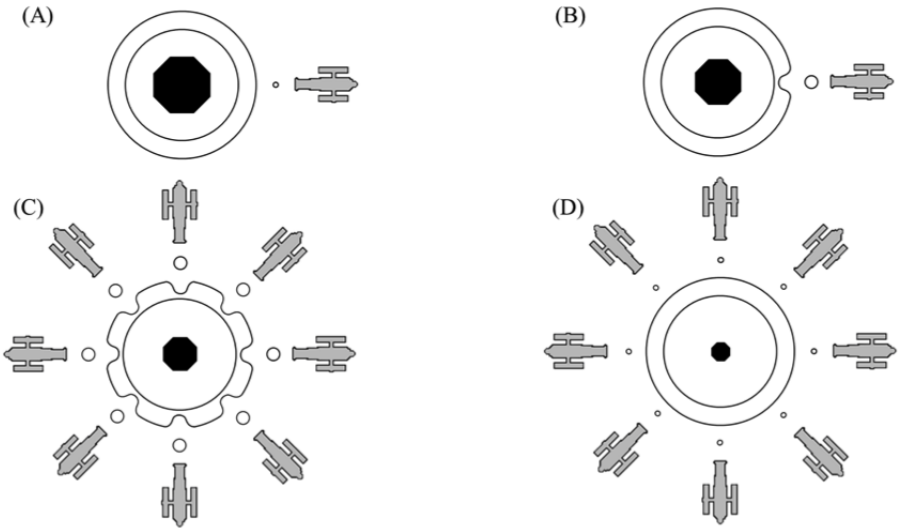

Figure 1: Scenario diagrams used in the Verbal + Diagram condition. Participants are presented with the scenarios in sequential order, accompanied by an auditory-verbal explanation of key concepts. (A) In scenario 1, a single cannon fires at the enemy octagon with small cannonballs and inflicts no damage to either the barrier or octagon. (B) In scenario 2, a single cannon fires at the octagon with large cannonballs, inflicting minor damage to the octagon but critically damaging the barrier in the process. (C) In scenario 3, multiple cannons fire at the octagon from different directions with large cannonballs, this time inflicting major damage to the octagon, but again critically damaging the barrier. (D) In scenario 4, multiple cannons fire at the octagon from different directions, but this time with small cannonballs. The cannonballs inflict no damage to the barrier, but are able to defeat the octagon by converging upon their target simultaneously, inflicting a moderate amount of damage.

response question per scenario). Both multiple-choice and free-response questions were administered using Qualtrics, an online survey environment intended for research and experimental purposes.

Next, each subject completed an abridged, twelve-item version of the Raven's Progressive Matrices test (RPM; Arthur, Tubre, Paul & Sanchez-Ku, 1999). The abridged RPM test served as a filler task to create a delay (approximately 10-15 minutes) between presentation of the source and target analogs. Moreover, the test provides a measure of fluid intelligence, allowing us to assess potential individual differences in transfer performance.

Finally, transfer rates to the radiation problem (Duncker, 1945) were measured across varying conditions of source training. Participants were asked to solve Duncker's radiation problem in a 2-pass fashion (cf. Gick & Holyoak, 1980). On the first pass, participants received no indication that the previously-presented scenarios were related to the target problem. After the participant submitted his answer, the radiation problem was presented again, but this time with an explicit hint to recall the four previous cannon scenarios and any solutions they might suggest.

Results

Analogical Transfer Rates

A set of criteria was adopted from previous research (Gick & Holyoak, 1980) to determine whether participants successfully solved the radiation problem either before or after the hint. Solutions were scored according to whether participants conveyed at least two of the three critical ideas underlying the convergence principle–i.e., *multiple* radiation sources are needed, radiation sources should fire *low-intensity* rays, and radiation sources should be positioned in different locations *surrounding* the patient's stomach tumor. Participants were scored as having either (1) successfully solved the radiation problem spontaneously (i.e., without the hint), (2) successfully solved the radiation problem with the hint, or (3) failed to solve the radiation problem. Two researchers naïve to the experimental hypothesis independently scored each participant's responses, with an agreement rate of 95% (Cohen's κ = .87). A third researcher broke the tie if the first two researchers disagreed with one another.

Spontaneous transfer rate corresponds to the percentage of participants who produced the convergence solution to the radiation problem *before* a hint was given to recall the source analog. This measure assesses participants' ability to spontaneously retrieve the source analog and apply their knowledge to a novel target problem. Total transfer rate corresponds to the percentage of participants able to solve the radiation problem either before or after a hint was given. Figure 2 depicts percentage of spontaneous transfer before a hint, and total transfer percentage after a hint for each condition (42 participants per condition). The spontaneous transfer rates were 55%, 50%, and 81% for the Verbal, Verbal + Diagram, and Verbal + Animation conditions, respectively. The spontaneous transfer rate in the Verbal + Animation condition exceeded that obtained in the Verbal + Diagram ($\chi^2(1) = 8.90$, $p = .003$) and Verbal conditions ($\chi^2(1) = 6.60$, $p = .01$), indicating that animated source instruction facilitated spontaneous analogical inference. Spontaneous transfer rate did not differ significantly between the Verbal and Verbal + Diagram conditions ($\chi^2(1) < 1$), suggesting that the addition of a static pictorial display was not effective in priming the temporally dynamic convergence principle. The total transfer rates after the hint were 83%, 69%, and 90% for the Verbal, Verbal + Diagram, and Verbal + Animation conditions, respectively. Results are consistent with previous findings in that roughly 80% of people were able to solve the radiation problem following a hint to think back to a relevant source analog (Gick & Holyoak, 1980, 1983). The total transfer rate in the Verbal + Animation condition exceeded that found in the Verbal + Diagram condition ($\chi^2(1) = 5.97$, $p = .02$), but did not differ from that found in the Verbal condition ($\chi^2(1) < 1$).

Understanding of Source Analog

To assess whether the advantage of the Verbal + Animation condition in supporting spontaneous transfer was linked to deeper understanding of the source analog, we evaluated participants' responses to multiple-choice (MC) and free-response (FR) source understanding questions. The four FR questions assessed participants' understanding of *why* the cannon(s) failed or succeeded in each scenario. For FR responses, three key principles were chosen for each scenario–e.g., the cannonballs were too large, or there were not enough cannons. Participants received one point for each correctly conveyed principle and had one point deducted for each incorrect idea they stated. For each response, participants with two or more points were given a score of 2, participants with one point were given a score of 1, and participants with zero points or less were given a score of 0. The FR responses in each scenario were scored by two researchers. A third scorer was employed for those responses where the first two disagreed. If two of the three scorers agreed, their score was used. If the three scorers disagreed, the response was jointly discussed until two researchers agreed on a score. The agreement rate for the first two scorers was 80% (Cohen's $\kappa = .62$). The agreement rate for the three scorers (i.e., cases where two of the three scorers agreed) was 95%.

The eight MC questions aimed to measure participants' understanding of how the small and large cannonballs interact with the various elements in the system, and how their forces sum together across scenarios. Each MC question was scored as either correct or incorrect, according to whether the participant selected the correct amount of damage inflicted to the specified element by the cannon(s). Participants received a score between 0 and 8 for each of the FR and MC source understanding measures.

FR and MC scores were correlated across participants ($r = .47$, $p < .001$). For FR scores, participants in the Verbal + Animation condition scored higher than those in either the Verbal + Diagram ($t(82) = 2.12$, $p = .04$) or Verbal conditions ($t(82) = 3.99$, $p < .001$). Those in the Verbal + Diagram condition also scored higher than participants in the Verbal condition ($t(82) = 2.35$, $p = .02$). For MC scores, participants in the Verbal + Animation condition scored higher than those in either the Verbal + Diagram ($t(82) = 2.76$, $p = .007$) or Verbal conditions ($t(82) = 4.02$, $p < .001$), whereas there was no significant score difference between Verbal + Diagram and Verbal participants ($t(82) < 1$). The consistent superiority of the

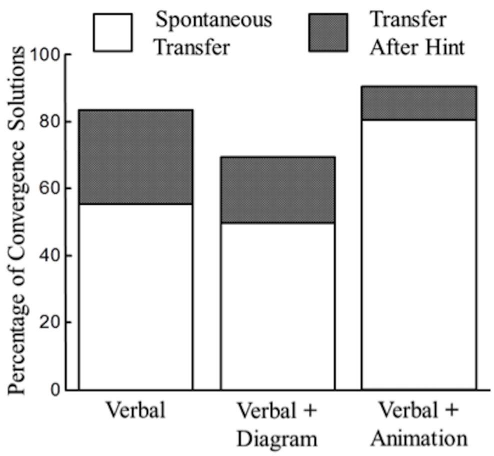

Figure 2: Percentage of convergence solutions generated before and after hint for Verbal, Verbal + Diagram, and Verbal + Animation conditions. Total transfer corresponds to height of entire bar.

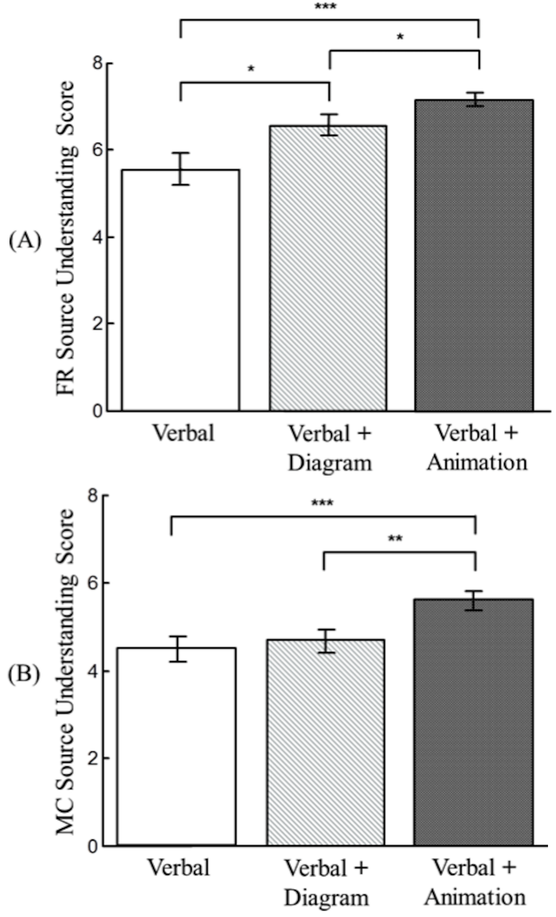

Figure 3: (A) Free-response and (B) multiple-choice source understanding score for Verbal, Verbal + Diagram, and Verbal + Animation conditions.

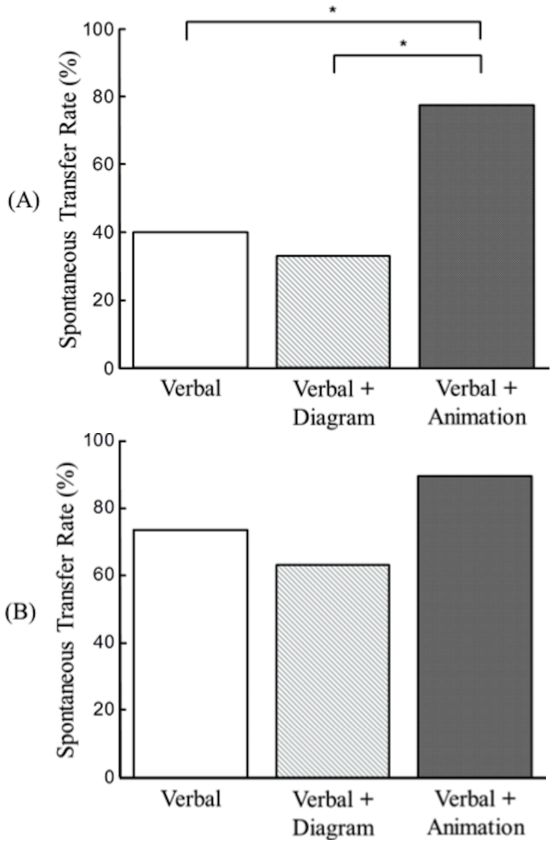

Figure 4: Spontaneous transfer rate (percentage of convergence solutions generated before hint) for (A) low-RPM and (B) high-RPM participants in Verbal, Verbal + Diagram, and Verbal + Animation conditions.

animation condition in both FR and MC responses indicates that the addition of animation led to deeper understanding of the source analog relative to other presentation methods (see Figure 3).

Individual Differences in Analogical Transfer

To assess whether the impact of source presentation was influenced by a measure of fluid intelligence, we performed a median-split on participants according to their Raven's score, classifying them as either low (Raven's score < 8) or high (Raven's score > 8) on the RPM test. Forty-five participants were classified as low-RPM and 57 participants were classified as high-RPM. The other 24 participants had median Raven's scores (Raven's score = 8); they were dropped from the individual differences analysis as they could not be reasonably classified as either high or low.

Spontaneous transfer rates were compared across conditions for the low and high-RPM subgroups (see Figure 4). For low-RPM participants, the spontaneous transfer rate for the radiation problem in the Verbal + Animation condition exceeded that obtained in the Verbal + Diagram ($\chi^2(1) = 5.93$, $p = .02$) and Verbal ($\chi^2(1) = 4.89$, $p = .03$) conditions. No difference was observed in transfer performance between the Verbal + Diagram and Verbal conditions ($\chi^2(1) < 1$). This pattern is consistent with the global pattern across all participants. For high-RPM participants, the spontaneous transfer rate in the Verbal + Animation condition was marginally greater than that in the Verbal + Diagram condition ($\chi^2(1) = 3.64$, $p = .06$), but did not differ from that in the Verbal condition ($\chi^2(1) = 1.58$, $p > .05$). The transfer rate in the Verbal + Diagram condition also did not differ from that in the Verbal condition ($\chi^2(1) < 1$). Thus, the benefit of animation in fostering spontaneous analogical transfer was greatest for those participants scoring relatively low on our measure of fluid intelligence.

Discussion

The present study found that animated source analogs yielded greater spontaneous transfer than either diagrammatic or purely verbal source analogs. These findings are consistent with those of Beveridge and Parkins (1987) and Pedone et al. (2001). The present study went beyond prior work by measuring the impact of varying presentation conditions on source understanding. We found that animation leads to superior source understanding as well as greater spontaneous analogical transfer. The benefit of animation in promoting an abstract understanding of the source may be similar to the benefit of comparing multiple source analogs, which appears to foster induction of a more abstract schema (Gick & Holyoak, 1983; Novick & Holyoak, 1991). The inherently dynamic nature of animation may be especially effective in inducing a dynamic schema for problems involving the application of forces over time and space. It is possible that an animated source induces internal scan patterns across a mental image of the target problem that facilitate transfer (analogous to benefits conveyed by certain patterns of over eye movements across a diagram of the radiation problem; Grant & Spivery, 2003; Thomas & Llereas, 2007).

In contrast to the apparent benefit of adding an animation to a verbal source representation, supplemental static diagrams were not effective in increasing transfer performance either before or after their relevance was pointed out. This appears to be inconsistent with the findings from our free-response measure, where adding a diagram appeared to improve source understanding. To account for this discrepancy, it should be noted that source understanding was measured *before* the RPM (filler) task. Thus, we do not know whether the initial benefit of static pictorial representations in source understanding survived the potential interference created by the RPM questions. Also, it is possible that although static diagrams effectively demonstrate certain properties of the source system, they do not effectively convey the dynamic convergence principle, which is crucial in solving the target problem.

Overall, supplemental animations led to deeper source understanding and greater spontaneous analogical transfer than did supplemental static diagrams or verbal representations alone. Analyses of individual differences in cognitive ability, as assessed by scores on an abridged Raven's Progressive Matrices test, indicated that animation is especially helpful for participants with relatively low RPM scores. This finding suggests that dynamic displays may be especially useful in teaching relational concepts and their generalization to students at lower ability levels. Providing these students with more robust representations of a novel source analog may reduce working-memory demands, thereby fostering analogical transfer. Future work should focus on how dynamic schemas can be learned from animations, perhaps by extending current theories of relation learning (e.g., Lu, Chen & Holyoak, 2012) to analogical transfer.

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