THE BENEFITS AND CHALLENGES OF ANALOGICAL COMPARISON IN LEARNING AND TRANSFER: CAN SELF-EXPLANATION SCAFFOLD ANALOGY IN THE PROCESS OF LEARNING?

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Abstract

There is ample evidence that analogy can be employed as a powerful strategy for learning new concepts, transferring knowledge, and promoting higher level thinking. Similarly, self-explanation has been shown as an effective strategy in learning, integrating new information with prior knowledge, and monitoring and revision of previous mental models (Chi et al., 1989). While both of these strategies are considered efficient scaffolding in the field of instruction and learning, each individual strategy has its own limitations and constraints such as overgeneralization, disregarding details, and possible erroneous reasoning. To investigate whether these constraints can be overcome, this paper initially reviewed and analyzed the benefits and challenges of using analogies in learning. It then discussed the potential benefits of integrating analogies and self-explanation. The resulting hypothesis was that prompting learners to explain analogical cases (analogy induced self-explanation) may greatly enhance learning through activation of prior knowledge, structured linking, categorical learning and higher order thinking. This integration may also lead to a revised model of self-explanation with higher productivity and less constraints on the process of knowledge acquisition and generalization.

Keywords: analogical comparison, self-explanation, scaffolding

The Benefits and Challenges of Analogical Comparison in Learning and Transfer: Can Self-Explanation Scaffold Analogy in the Process of Learning?

During the past three decades many instructional theories and techniques have evolved to explain how learning occurs and what instructional strategies facilitate this process. Some of these evidence-based strategies are practice, worked-out examples, learning by discovery, problem-based learning, analogy, and self-explanation (Baron et al., 1998; Nokes & Ohlsson, 2005; Atkinson et al., 2003; Sweller & Cooper, 1985; Gentner et al., 2003; Gick & Holyoak, 1983; Chi et al., 1989; Chi et al., 1994; Rittle-Johnson, 2006). While each individual technique has been well addressed in literature and the similarities and differences across techniques have been analyzed, the integrative role of some of these strategies such as analogy and self-explanation has not been well addressed. Therefore, it is plausible to investigate the cumulative effects of such instructional techniques on various stages of learning process, such as knowledge acquisition, schema formation, problem solving, retention, and transfer.

The main goal of this paper is to investigate how analogy can improve learning and whether the integration of self-explanation with analogy can improve the efficiency of analogy as an instructional strategy. This review begins with identifying the processes that support and limit the role of analogical comparison in learning. It then examines the scaffolding mechanisms of self-explanation in learning and the constraints on its applicability. These two sections set the stage for the last component of the paper which will hypothesize the joint effects of both strategies and elaborate on the significance of eliciting explanation based on provided analogical cases. This investigation will be based on three principles: (1) each scaffolding method is highly effective independently of the other (2) self-explanation theory and analogical reasoning have strong theoretical and empirical support in literature and have been employed as effective psycho-educational mechanisms in learning and transfer in various domains and (3) Both strategies have limitations.

Analogical Comparison

Gentner (2003) defines analogical comparison as comparing two domains with structural similarities, with or without shared surface features. The familiar concept is often called the *source* and the unfamiliar concept is called the *target* (Glynn, 1991). For example, in the Rutherford's Model of atom, the solar system and atom are considered as the source and target respectively as they are constructed in similar structural fashion with shared common relational roles – the sun and the nucleus are both the larger object in the center and the electrons and planets revolving around them.

According to this definition, the strength of an analogy depends on the overlapped shared features that serve the goal of the analogy. For example, in the analogy between a battery and a reservoir, the analogy does not depend on the overlapped features such as the shape or size of the analogs. The strength of the analogy comes from the shared underlying property of potential energy that can be stored and released to supply power to the related systems (Gentner, 1983).

While Gentner (Gentner, 1992, 1983) agrees that the key similarities in analogy are determined by the *relations* that hold within the domains. She argues that the actual power of analogy depends on relations that exist between relations, referred to as *higher order relations*. For example, in a simple analogy between the flow of electrons in an electric circuit and the flow of people in a congested subway tunnel, the analogy becomes enriched when an inserted narrow gate into the tunnel is mapped to an inserted resistor into a simple electric circuit (as cited in Holyoak et al., 2001). In the same way that a narrow gate would cause a decrease in the rate of flow of people, an added resistor would cause a decrease in the flow of electricity. This added component leads to a relational explanation that is crucial to deeper understanding of the compared phenomena and/or analogs. Therefore, it is crucial to find a matching set of relations that are interconnected by higher order relations, such as causal, mathematical, and functional, in order to create a high quality analogical match (Celement & Gentner, 1991; Markman & Gentner, 1993).

The *structural mapping theory* of Gentner (1983) generalizes the above definitions to two principles of *structural alignment* and *systematicity* in all analogical comparisons. A structural alignment between domains is the formation of one-to-one correspondence between the mapped elements (structural parallelism) and systematicity is the creation of higher-order relations among the domains such as causal chains or chains of implications. By this theory, not all similarities between situations can be qualified as analogy (Clement & Gentner, 1991) and the efficiency of analogy as learning and retrieval mechanisms depends on the complexity of these two constraints. Similarly, Holyoak and Thagard (1997) explain analogy as a process constrained by three constraints of similarity, structure, and purpose – the *multiconstraint theory* – and argue that analogical thinking can be much more influenced by structure and purpose than by superficial similarities. In this paper, the benefits and limitations of analogy as a cognitive mechanism are analyzed based on both structural mapping and multiconstraint theory.

Analogy as a Learning Mechanism

A recent meta-analysis conducted by Alfieri et al. (2013) indicates that analogical comparison, in both classroom and laboratory setting, leads to more improved learning outcomes than instruction that is based on sequential, single, or non-analogous cases ($d = 0.50$). In fact, many experimental studies indicate that analogy can improve learning through schema induction, transfer of learning, promoting higher order thinking, and correcting misconceptions. However, as Duit et al. (2001) argue, analogies are double-edged swords that can promote understanding and also lead to misconceptions. In this section, some of the advantages and limitations of this instructional strategy will be analyzed. Self-explanation will then be introduced as a scaffolding strategy that can be employed along with analogy to improve its limitations and function as a synergistic factor.

Schema induction

One way in which schemas can be acquired is through analogical comparison (Gick & Holyoak, 1983). When the structures of two cases are compared through aligning and mapping, a relational abstraction is developed by extracting the shared relational commonalities and discarding the non-related contextualized features. Although this schematic knowledge consists of some superficial similarities, it is mainly constructed based on the key relational features that are *causally* connected to the goal of the analogy. This schema, which includes the abstractions or deep knowledge of the problems and the solution principles in thinking by analogs, is then preserved and stored in the memory (Murphy & Panchanadam, 1999; Brown & Clement, 1989; Gick & Holyoak, 1980; Gick & Holyoak, 1983) and recalled later in structurally similar situations.

This constructive process is not limited to two relational analogs only and can be further expanded by providing more than two analogs (Cartambone & Holyoak, 1989). In fact, Gick and Holyoak (1983) argue that encouraging comparison of multiple source analogs fosters abstraction of a more generalized schema and improves the chance of recognizing the structural similarities among the problems. This is particularly true if the analogy is followed by a representation of the solution principle (confirmation of abstraction).

Transfer forward and backward

Transfer often occurs after examples or analogical cases are abstracted into schemas and the similarities of their schemas are recognized (Murphy& Panchanadam, 1999). Therefore, schema induction is considered as a facilitator of analogical transfer (Gick & Holyoak, 1983). According to Gentner et al. (2004), it is the *analogical encoding* – an explicit comparison of two partially understood situations – that leads to identification of common principles and transfer of the common principles to structurally similar contexts. In fact, experimental findings indicate that analogical encoding not only facilitates transfer to future structurally similar cases (forward transfer), but also the retrieval of prior structurally similar cases from memory (backward transfer).

The *cause-and-effect relation* in the source and target is another essential factor for achieving the transfer goal of analogy (Holyoak & Richland, 2014). An experiment on analogous "convergence" problems conducted by Gick and Holyoak (1983) indicates the role of such relationships in transfer vividly. In their experiment, learners had to find an efficient radiation strategy to destroy a stomach tumor without destroying surrounding healthy tissues. In one condition, one analogous example was studied and in the other condition two analogous examples were compared before attempting to respond to the convergence problem. In the two-example-comparison group, the participants compared the strategy that a general would use to divide his army into small groups to simultaneously attack the fortress and the firefighters who would use a number of small hoses to extinguish a centrally located fire.

According to the results of the study, participants who compared the two analogs demonstrated significantly more transfer than those who were provided with only one source analog. The comparison between the two analogs led to the solution of sending multiple low-intensity rays directed at the tumor from various directions. In this way the healthy tissue could stay unharmed while the effects of numerous low-intensity rays would accumulate and destroy the tumor. Similar results were also found in other studies such as business students who learned negotiation strategies through comparing multiple cases in their training (Gentner et al., 2003) and students who managed to transfer problem concepts in mathematics, physics, and natural sciences (Rittle-Johnson & Star; Richland et al., 2007; Alfieri et al, 2013). Holyoak and Richland (2014) argue that analogy prepares learners to transfer knowledge *flexibly* from one or multiple sources to a target. This flexibility allows application of the learned principles to cases that are new and require high level of modification. It also fosters cognitive readiness for applying one's prior knowledge in an adaptive manner and transfer knowledge successfully to novel situations (Holyoak et al., 2010; Lee & Holyoak, 2008).

Developing higher order cognition and expert-like thinking

Higher order thinking and lower order thinking have been described in different ways in literature (Lewis and Smith, 1993). Maier (1933, 1937) uses the term *productive reasoning* for higher order in contrast with learned behavior or *reproductive thinking* for lower order thinking. According to this definition, memorizing the multiplication tables through repeated practice would be considered a lower order thinking while tasks requiring metacognition, making inferences, generalization across contexts, and synthesizing information are considered higher order thinking skills (Pogrow, 2005). By this definition, a child who knows how to compute the area of a rectangle and uses that information to compute the area of an unknown shape, such as a parallelogram, is engaged in higher order thinking. Since he or she needs to convert a parallelogram to a rectangle of the same area and discover the formula for the area of a parallelogram. This type of thinking is often the result of *comparing* and *relating* new and stored information in memory (Lewis & Smith, 1993; Richland & Simms, 2015) and is achieved through accurate analogical reasoning.

Reducing misconceptions and conceptual change

Analogy can be an effective strategy to change students' misconceptions if it is built on *correct* prior knowledge. Therefore, in analogical instruction, the goal is to increase the possibility of application of the correct intuition and decrease the possibility of using detrimental intuitive concepts. To ensure that this change occurs, multiple analogical connections among various intermediate cases need to be established so learners who cannot view the initial cases as analogous can extend their valid intuitions. This extension is called *bridging* analogies (Brown & Clement, 1989) and appears to be highly effective in reducing misconceptions in science courses. For example, for many introductory physics courses, misconceptions about the existence of an upward force on a resting object can be addressed by providing *anchor* examples that appeal to student's intuition. This can be done by placing a book on a spring and then both of them on a flexible table so students can see the table as an active object that can exert an upward force to the book. This bridging step can make the original target more clear and reachable and, therefore, can make learning more effective. Brown and Clement (1989) propose four mechanisms for this effectiveness: anchoring example, bridging analogies, engagement in the process of analogy, and the enrichment of the target. These four factors lead to construction of a new explanatory model and, consequently, a deep conceptual change.

In a similar study conducted by Schollum et al. (1981), analogy was employed to correct student misconception of innate power in moving objects. The researchers used the misconception to introduce the concept of "force" and differentiated it from "momentum."

Analogical Comparison Challenges

Research on analogy has identified several specific areas in which analogy may break down and interfere with a successful learning process. Some of the challenges that emerge from the experimental literature include the following.

Lack of recognition of relational correspondences

Learners may not be able to identify analogies or the benefits of making an analogy despite available relational similarities (Richland & Simms, 2015; Vandetti et al., 2015). This is particularly true for young children and domain novices who tend to notice similarities between sets, problems, or concepts based on object properties rather than the relationships within the representations. An example of this case is when learners notice similarities in the appearance of various polygons and not the relations between their angles and line segments (Mix, 1999; Ross & Kennedy, 1990).

Strong dependency of analogy on relevant pre-existing knowledge

The efficient use of analogy depends on having adequate prior knowledge. It is only by activating the relevant prior knowledge which is already understood by the learner, analogy can make the incoming information meaningful (Royer & Cable, 1975; Mayer 1989; Stepich & Newby, 1988). In the studies conducted by Rittle-Johnson and Star (2007) and Start and Rittle-Johnson (2009), the participants who did not have any intuition about solving algebraic problems on the pretest could not benefit from analogical examples and mostly benefited from separate and sequential solution strategies. On the contrary, the participants with partial prior knowledge in algebra highly benefited from simultaneous examples and solutions.

Incoherence and gaps in knowledge can also be the major determinants of failing to understand analogies. As Booth and Koedinger (2008) argue, incoherence and gaps in knowledge can interfere with the learner's ability to identify similarities across examples and, therefore, push the learner towards more superficial features.

High cognitive load of analogical processes

Learners may be hindered by the high processing demands of extraction and elimination involved in structural mapping understanding (Mix, 1999; Reed, 1987; Zook & Vesta, 1999).

Representing information as integrated relational systems and then aligning, mapping, and drawing inferences based on these systems all require working memory and inhibitory control resources (Cho & Holyoak, 2007). Both children and adults fail to reason relationally when working memory load is high (Morrison et al., 2011), inhibitory control demands are excessive and the domain knowledge is limited. Thus, as recommended by the cognitive load theory (CLT), instructional methods should avoid overloading the memory to maximize learning (Sweller, 1988).

Mechanical use of analogy

Another possible challenge in learning by analogy is promoting the mechanical use of analogy in learners and oversimplifying complex concepts. Analogies encourage learners to reduce complex concepts into simpler and more familiar ones (Spiro et al, 1989). Sometimes it is more convenient for students to think of a concept as a familiar analogy than to dedicate an immense amount of time to learn a new rational explanation or develop a precise understanding of the new concept (as cited in Orgill & Bodner, 2004). This dependency on simplification of complex contents may lead to lack of effort to generate explanation. In fact, Spiro et al. (1989) noticed that medical students who had been exposed to analogies in their instruction did not have a deep understanding of some biological concepts such as myocardial function and failure.

Integration of Self-explanation Prompts for Scaffolding Analogy

Analogies can be powerful tools for creating adaptable conceptual knowledge (e.g. Clement, 1993; Gentner et al., 2003; Rittle-Johnson & Star, 2007). However, the challenges such as inadequacy of relevant prior knowledge, high cognitive processing load, and lack of recognition of the causal relations in analogy may disrupt the learner's ability to identify similarities across examples (Booth & Koedinger, 2008; Richey & Nokes-Malach, 2015). Additionally, analogies that depend on superficial features may increase misconceptions by leading the learner to infer relationships that may not exist in similar situations (Markman & Gentner, 1993). Research shows that learners who do not have enough expertise or instructional support often fail to gain any benefits from analogical instruction (Bransford, Brown & Cocking, 1999; Gentner & Rattermann, 1989; Gick & Holyoak, 1980, 1983; Bassok & Holyoak, 1989) and my develop limited transfer ability.

Therefore, instruction through analogy requires explicit support to ensure that learners notice the relevance of relational thinking, hold and manipulate relations, and consider both similarities and differences when drawing analogies (Richland & Simms, 2015). Harrison and Col (2008) argue that application of analogy can be greatly enhanced if more attributes across the two domains are mapped and if the ways in which the source and target are similar can be explained. Therefore, one of the effective strategies to scaffold relational thinking is to provide learners with self-explanation prompts at various stages of analogical reasoning process. Since the core cognitive mechanisms of self-explanation are based on inference generation to fill in the missing information, integration of new information with prior knowledge, and monitoring and repairing inaccurate knowledge (Roy & Chi, 2005), self-explanation can make analogy more known to the learner, improve understanding of the source, and make mapping more valid.

Many studies support the role of explanation in improving learning by analogy. For instance, when business students were prompted to write down their explanation of commonalities among various negotiation strategies, they ended up with a substantial transfer of proper strategies in actual face-to-face bargaining sessions (Gentern et al. in 1999, 2000, and 2003). These results are also consistent with the experiment conducted by Gick and Holyoak (1983) on tumour destruction. The participants who explicitly explained the key aspects of the convergence solution in terms of the similarities between the analogs showed spontaneous transfer to the tumor problem. It seems that the constructive activity of self-explanation (Roy & Chi, 2005) helps learners direct their attention to specific aspects of causal relations and allow them to think about the new material in a transformative and constructive manner (Chen & Brashaw, 2007).

Other studies in literature also indicate that students can perform more efficiently at problem-solving tasks, generating inferences, and repairing flawed mental models when they use self-explanation strategy during learning. These effects have been observed in mathematics (Siegler, 2002; Wong et al., 2002), programming (Pirolli & Recker, 1994), physics (Mayer et al., 2003), biology (Chi et al., 1994; Neubrand & Harms, 2016), and clinical reasoning (Chamberland & Mamede, 2015).

Discussion

Analogy is a powerful cognitive strategy (Gentner & Holyoak, 1997) that operates at two levels. In simple descriptive analogies, one or more superficial attributes of the source correspond with the target and in more complex inductive analogies many features both at superficial and higher-order causative relations are shared (Harrison & Treagust, 1994; Gentner, 1994).

Using analogies in learning can effectively improve inference making and abstract reasoning (Hoyos & Gentner, 2017) in areas such as problem solving (Gick & Holyoak, 1980), forward and backward transfer (Nokes-Malach et al., 2013) and higher order thinking. Analogies can also be detrimental to learning if not employed correctly. As Duit et al. (2001) argue, analogies can lead to misconceptions due to the factors, such as inadequate prior knowledge, lack of clear understanding of the source, invalid mapping, and high cognitive processing demanded by the task. This paper argues that scaffolding strategies, such as self-explanation prompts, can be highly effective in increasing the effectiveness of analogy as a learning strategy. The rationale for this argument is based on two important cognitive mechanisms of self-explanation, namely, gap filling in the provided text or examples (Conati & VanLehn, 2000; Hausmann & Chi, 2002) and inconsistency revision in prior knowledge (Chi et al., 1994; Hausmann & VanLehn, 2007). The gap filling mechanism of self-explanation allows justification of the provided content and fills in the missing information. Therefore, it is highly useful when the learner has little relevant prior knowledge (Hausmann & Chi, 2002; Nokes et al, 2011). On the other hand, mental model revising mechanism focuses on connecting prior knowledge to the provided content and addresses the conflicts between the two (Chi, 2000). These strategies can scaffold analogical reasoning by encouraging learners to identify the critical features of problems, including their underlying principles (Atkinso et al., 2003; Chi & VanLehn, 1991), the conditions for applying the principles (Chi et al., 1989), and the rationale for application of the principles (Catrambone, 1998; Crowley & Siegler, 1999).

It seems reasonable that self-explanation and analogical comparison can be combined for additional gains (Hoyos & Gentner, 2017). However, a coherent set of principles for integrating analogy into learning via self-explanations need to be developed, implemented, and tested in future studies.

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