Cognitive Science 27 (2003) 669–681

COGNITIVE SCIENCE

http://www.elsevier.com/locate/cogsci

The effects of self-explaining when learning with text or diagrams

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Received 19 September 2002; received in revised form 17 December 2002; accepted 2 February 2003

Abstract

Self-explaining is an effective metacognitive strategy that can help learners develop deeper understanding of the material they study. This experiment explored if the format of material (i.e., text or diagrams) influences the self-explanation effect. Twenty subjects were presented with information about the human circulatory system and prompted to self-explain; 10 received this information in text and 10 in diagrams. Results showed that students given diagrams performed significantly better on post-tests than students given text. Diagrams students also generated significantly more self-explanations that text students. Furthermore, the benefits of self-explaining were much greater in the diagrams condition. To discover why diagrams can promote the self-explanation effect, results are interpreted with reference to the multiple differences in the semantic, cognitive and affective properties of the texts and diagrams studied.

Keywords: Learning; Self-explanation; Representations; Diagrammatic reasoning

1. Introduction

Students develop a deeper understanding of material they study if they generate explanations to themselves whilst learning. Chi, Bassok, Lewis, Reimann, and Glaser (1989) gave subjects learning mechanics worked-out examples containing text and diagrams. Students who spontaneously generated a large number of self-explanations scored over twice as highly on a post-test as those who gave fewer explanations. Students benefit by self-explaining when prompted by humans (Chi, Deleeuw, Chiu, & Lavancher, 1994) and computers (Aleven & Koedinger, 2002),

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0364-0213/03/$ – see front matter © 2003 Cognitive Science Society, Inc. All rights reserved.
doi:10.1016/S0364-0213(03)00033-8

and this skill can be taught (Bielaczyc, Pirolli, & Brown, 1995). The self-explanation effect is observed in a wide variety of domains from physics problem-solving to geometry and programming. But does the way that material is represented influence learners' self-explanations? Studies have either presented material as text (e.g., Chi et al., 1994) or in text and diagrams (e.g., Aleven & Koedinger, 2002; Chi et al., 1989). Yet there is considerable evidence to suggest that the format of information influences learning. This experiment examined the self-explanation effect when learners study the human circulatory system with either text or diagrams.

1.1. Learning with text or diagrams

Graphical representations preserve geometric and topological information, whereas text has an arbitrary relationship to the object that it represents (e.g., Larkin & Simon, 1987; Schnotz, 2002). There is abundant evidence that presenting information either graphically or textually influences learning. Scaife and Rogers (1996) proposed that graphical representations bring advantages for learning by computational offloading, re-representation and graphical constraining:

Computational offloading is the extent to which different external representations reduce the amount of cognitive effort required to solve equivalent problems. For example, Larkin and Simon (1987) showed how search processes are considerably more efficient in diagrammatic rather than textual representations and proposed that text often has a high cost of perceptual enhancement.

Re-representation refers to the way that alternative external representations that have the same abstract structure, differentially influence problem-solving. Zhang and Norman (1994) showed that problem-solving with isomorphic versions of the Towers of Hanoi was enhanced when representations externalized more information. By utilizing external perceptual processes rather than cognitive operations, graphical representations will often be more effective.

Graphical constraining describes the limits on the range of inferences that can be made about the represented concept. Stenning and Oberlander (1995) argue that text permits expression of ambiguity in the way that graphics cannot easily accommodate. It is this lack of expressiveness that makes diagrams more effective for solving determinate problems.

1.2. Text, diagrams and self-explanation

Cox (1999) proposes that diagrams will facilitate the self-explanation effect. He argues that as graphical representations act to constrain interpretation by limiting abstraction, they provide learners with more salient and vivid feedback to compare against their explanations. However, Wilkin (1997) argues that diagrams may inhibit the self-explanation effect. She presented participants with textual worked-out examples from which they had to draw diagrams of two-dimensional motion. She found no self-explanation effect and concluded that diagrams, by invoking familiar but erroneous knowledge, encouraged students to generate incorrect self-explanations.

The role that self-explanation can play in multi-representational understanding has also been considered. Aleven and Koedinger (2002) argue that self-explanations prove particularly beneficial if they help integrate visual and verbal knowledge. Novice learners rely on visual information in geometry problem-solving, with fragmented visual and verbal declarative knowledge. Self-explaining helps these learners to strengthen their verbal declarative knowledge and integrate it with visual knowledge. Cox (1999) proposes that translation across modalities (e.g., verbal explanations with graphical representations) will lead to greater understanding than translation within one modality (e.g., written text with verbal explanations).

This study set out to explore a number of related issues about the role of self-explaining when learning with text or diagrams.

(1) Do students learn more about the structure and function of the human circulatory system from diagrams or text?
(2) Do students learn more when they self-explain?
(3) Do students generate more self-explanations when they study diagrams or text? Students will be provided with either text or concrete diagrams, in contrast to Wilkin's study, where they were presented with text and drew diagrams. Cox (1999) suggests that diagrams, by the dual processes of reducing cognitive effort and graphically constraining learners' interpretation of the situation, will encourage self-explanations in the diagrams condition. Alternatively, if Wilkin's results generalize from constructed to presented diagrams, then diagrams may be associated with fewer self-explanations.
(4) Is self-explanation more beneficial for learning from diagrams or text? Aleven and Koedinger (2002) and Cox (1999) imply that self-explaining should aid understanding in the diagrams condition by helping learners to integrate visual and verbal knowledge. In the text condition, the effect may be less pronounced as the material and self-explanations use the same underlying form of representation. However, learners face considerable difficulties when translating between representations (e.g., Tabachneck-Schijf, Leonardo, & Simon, 1997) and translation can be more complex with representations of different formats (Ainsworth, Bibby, & Wood, 2002). Hence, many conflicting factors may interact to influence the self-explanation effect.

2. Method

2.1. Design

The experiment employed a two factor mixed design. The first factor was time (pre-test, post-test). The second factor, format, was between groups (diagrams or text). Participants were randomly assigned such that each condition had 10 males and 10 females. They ranged in age from 19 to 23 years and had not studied biology past the age of 16.

2.2. Materials

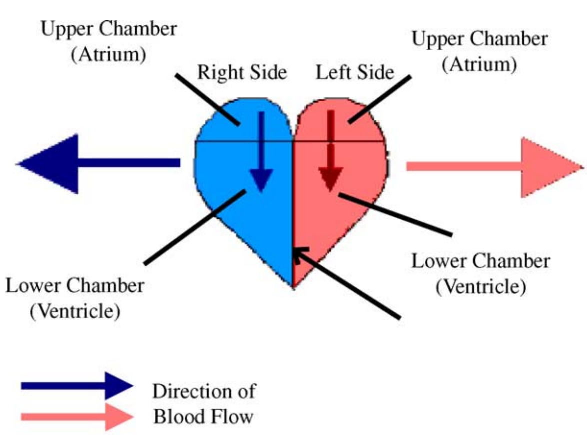
The passage about the human circulatory system used previously by Chi et al. (2001) was adapted for this study. Fifty-nine of the 86 sentences were included, which focused on the structure and functioning of the human circulatory system. The deleted sentences referred to ideas that could not be easily represented in diagrammatic form without additional text (e.g., "The English scientist William Harvey (1578–1657) first showed that the heart and blood vessels formed one continuous closed system of circulation"). The text was divided into 13 coherent sections.

Thirteen diagrams were constructed that corresponded to each section of text. Piloting ensured that the information presented in the text was inferable from the diagrams. However, it is impossible to claim that the text and diagrams are informationally equivalent. The specificity of graphical representations enforces a detail of information that is not present in the text. For example, no sentence in the text describes the relative size of the atria to the ventricles, but the information is inevitably present in a diagram. This is a fundamental difference between text and concrete diagrams. No test item required learners to reason about information only inferable from the diagrams.

Each diagram is a mix of text and pictures. Learners must study the pictures and/or integrate a textual key with an aspect of the picture (e.g., red or blue blood with text explaining that red is oxygenated and blue deoxygenated blood). Each diagram was printed on a separate sheet of paper (a single diagram could contain multiple graphics), and assembled in a file in the same order as the text (see Figs. 1 and 2).

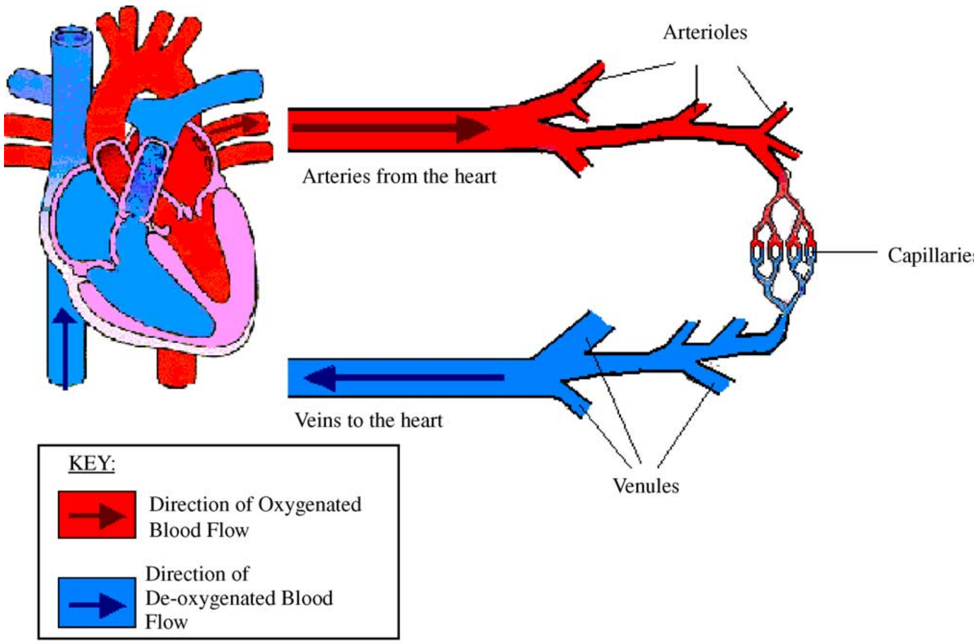
2.3. Pre-tests and post-tests

The pre-test and post-test were based on Chi et al.'s (2001) tests, which identify the knowledge each question assesses, and whether this information was given directly or whether a learner would need to infer it. These tests were adapted to address representational issues and the number of questions was reduced as the current experiment used less material.



- The septum divides the heart lengthwise into two sides.
- The right side pumps blood to the lungs, and the left side pumps blood to other parts of the body.
- Each side of the heart is divided into an upper and lower chamber.
- Each lower chamber is called a ventricle.
- Each upper chamber is called an atrium.
- In each side of the heart blood flows from the atrium to the ventricle

Fig. 1. General structure of the heart (diagram and text).



- The large, muscular vessels that carry blood away from the heart are called arteries.
- Blood travels through a network of smaller arteries, which in turn divide and form even smaller vessels called arterioles.
- The arterioles branch into a fan of tiny vessels called capillaries.
- De-oxygenated blood flows through capillaries that merge and form larger vessels called venules.
- Several venules in turn unite to form a vein, a large blood vessel that carries blood to the heart.

Fig. 2. Blood vessels (diagram and text).

2.3.1. Blood path diagram

Subjects were required to draw a blood path on the outline of a human body at pre-test and post-test.

2.3.2. Explicit questions

Ten questions can be answered by directly referring to the text or diagrams. Half the questions were presented diagrammatically and half textually. They took the form of multiple-choice questions with one correct and three incorrect items. The mode of presentation was counterbalanced for pre-test and post-test and varied between subjects.

2.3.3. Implicit questions

These six questions required students to integrate information from two or more lines of the text, or from different parts of diagrams, or to integrate across nonconsecutive paragraphs or diagrams (e.g., "Why is there an artery that carries deoxygenated blood?"). Each question was marked out of 2 (one point per correct concept).

2.3.4. Knowledge inference questions

Four questions required students to infer new knowledge from the sentences or diagrams to assess if students had developed a correct mental model, for example, "Why do we sometimes refer to the heart as a 'doublepump'?". Each question was marked out of 3 (one point per concept).

2.4. Procedure

Students worked individually with an experimenter to answer pre-test questions, study whilst self-explaining and respond to post-tests. The session took around 1 h.

2.4.1. Pre-tests

Participants were given the body outline and were told to draw the blood path to all parts of the body and that they could label the diagram or add a key. Then students answered the multiple-choice questions.

2.4.2. Study phase

Students were told that they would be presented with a paper file containing the texts or diagrams, which explained the human circulatory system. Students were asked to generate explanations to themselves whilst they were learning. The experimenter limited her prompts for self-explanation, only asking learners to self-explain if they became silent, or asked for further clarification if what they stated was vague. These prompts and self-explanations were audiotaped for later analysis and to record time on task.

2.4.3. Post-test

After studying the material, students immediately took a post-test. In addition to the pre-test material, it included the implicit and knowledge inference questions.

2.5. Coding of verbal protocols

Self-explanations were coded using the following scheme, based on Renkl (1997). However, it does not include anticipative reasoning, as this study did not address problem-solving.

2.5.1. Principle-based explanation

This category was scored if participants made reference to the underlying domain principles in an elaborated way (e.g., "*this is due to diffusion as molecules are spreading from a greater concentration to a lesser concentration*"). It corresponds to Renkl's coding of the learner's references to the principles of probability.

2.5.2. Goal-driven explanation

Self-explanations were classified as goal-driven if the student imposed a goal or purpose for an action; for example, inferring that the reason blood is being taken to the lungs is "*so that it* *can become oxygenated*". This category corresponds to Renkl's "Goal-operators combinations" category.

2.5.3. Elaboration of the problem situation

This category corresponds Renkl's and includes elaboration of the current sentence/diagram, for example, "*the network begins from the heart and then blood goes through the network*" and metaphors and analogies ("*have you ever seen part of a road where cars move in both directions? No! Why should blood*").

2.5.4. Noticing coherence

This indicates when students related what they were presently studying to a previous item, and is identical to Renkl's.

2.5.5. Monitoring negative/positive

Statements indicating that a student did not understand/understands the material.

The same rules were used for both the text and diagrams conditions. A statement was only coded as a self-explanation if it was not a paraphrase of text or a restatement of the information given in the diagram.

2.6. Learning outcomes

To examine the effects of format on learning, mixed (2×2) ANOVAs were performed on the blood path diagram and multiple-choice questions. The design of the analysis was format (diagrams, text) with a repeated measure of time (pre-test, post-test).

Analysis of the blood path diagram revealed significant main effects of time ($F(1, 18) = 45.47$, MSE $= 1.27$, $p < .0001$) and format ($F(1, 18) = 10.38$, MSE $= 1.89$, $p < .01$) modified by a significant interaction ($F(1, 18) = 15.47$, MSE $= 1.89$, $p < .001$). Simple main effects showed the only difference between the conditions was at post-test ($F(1, 36) = 24.85$, MSE $= 1.58$, $p < .001$); subjects in the diagram condition scored significantly higher (Table 1). Scores in diagram condition significantly improved over time ($F(1, 18) = 57.00$, MSE $= 1.27$, $p < .001$), whereas improvement for the text condition manifested as a trend ($F(1, 18) = 3.95$, MSE $= 1.27$, $p = .063$).

Analysis of explicit questions identified a significant main effect of time ($F(1, 18) = 89.08$, MSE $= 4.14$, $p < .0001$) and a significant interaction between format and time ($F(1, 18) =$

Table 1
Scores for blood path diagram and multiple-choice questions by format and time

	Blood path diagram (9)				Multiple-choice (10)			
	Diagrams ($n = 10$)		Text ($n = 10$)		Diagrams ($n = 10$)		Text ($n = 10$)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Pre-test	2.4	0.70	2.4	0.84	3.5	1.18	3.8	1.62
Post-test	6.2	1.81	3.4	1.35	8.0	1.56	5.6	2.01

Table 2
Scores for implicit and knowledge inference questions by format

	Implicit questions (12)				Knowledge inference (12)			
	Diagrams ($n = 10$)		Text ($n = 10$)		Diagrams ($n = 10$)		Text ($n = 10$)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Score	7.4	1.26	5.9	2.02	9.4	1.78	5.6	1.96

16.36, MSE = 1.11, $p < .001$). Simple main effects ($F(1, 36) = 10.97$, MSE = 2.63, $p < .003$) showed the only difference between the conditions was at post-test, with the diagram condition scoring higher. Both conditions improved over time-diagrams ($F(1, 18) = 91.00$, MSE = 1.11, $p < .001$) and text ($F(1, 18) = 14.54$, MSE = 1.11, $p < .002$).

Subjects' performance on the implicit questions showed a trend towards significance ($F(1, 18) = 3.95$, MSE = 2.85, $p = .062$) with students in the diagrams condition scoring somewhat higher on implicit questions (Table 2). Format had a significant influence on the knowledge inference questions ($F(1, 18) = 3.95$, MSE = 3.49, $p < .001$); scores in diagram condition were significantly higher.

2.7. *Self-explanations*

Students' self-explanations were then transcribed and analyzed. The second author coded all statements into either a type of self-explanation, monitoring statement or other phrase, which was almost always a paraphrase with the occasional off topic comment. These data are shown in Table 5. The first author recoded a random sample of 60% of the transcripts. Reliability between the codings assessed whether each statement was a self-explanation, a monitoring statement or other statement. Agreement between authors was found to be reliable ($K = 0.91$, $p < .001$).

Students who generated a greater number of self-explanations performed better at post-test (Table 3). Number of self-explanations was significantly negatively correlated with time spent learning and number of words. There was no significant relationship between pre-test scores and number of self-explanations.

Table 3
Correlations between number of self-explanations, total time spent learning, number of words, pre- and post-test scores

	2	3	4	5
(1) Number of self-explanations	−.06	.11	−.19	.50*
(2) Total time		.67**	−.26	−.69**
(3) Number of words			−.03	−.50*
(4) Pre-test total				.10
(5) Post-test total				

* $p < .05$ (two tailed test of significance).
** $p < .01$ (two tailed test of significance).

Table 4
Number of self-explanations, monitoring statements, words, and time to learn by format

	Diagrams ($n = 10$)		Text ($n = 10$)	
	M	*SD*	*M*	*SD*
Total self-explanations	10.7	4.0	6.4	3.8
Total monitoring	1.2	1.2	1.1	1.3
Number of words	909.0	215.8	1205.4	197.8
Time to learn (min)	15.9	2.3	24.4	5.0

Table 5
Mean number of types of statements by format

	Diagrams ($n = 10$)		Text ($n = 10$)	
	M	*SD*	*M*	*SD*
Principle based	0.7	0.67	0.0	0.00
Goal-driven	7.7	3.47	4.3	2.26
Elaborate conditions	1.6	0.84	1.4	2.07
Noticing coherence	0.7	0.67	0.7	0.67
Monitoring negative	0.5	0.71	0.9	1.20
Monitoring positive	0.7	0.67	0.2	0.42

The impact of format on the processes of learning was examined by two-way MANOVA with dependent variables of number of self-explanations, number of words and time to learn (see Table 4).

Students in the diagram condition generated significantly more self-explanations than those studying text ($F(1, 18) = 6.06$, MSE $= 15.25$, $p < .025$), but spent significantly less time studying the material ($F(1, 18) = 23.62$, MSE $= 15.29$, $p < .001$) and spoke significantly less ($F(1, 18) = 10.26$, MSE $= 42,832$, $p < .05$). A Mann–Whitney test on the number of monitoring statements revealed no impact of format ($U = 46.5$).

The number of each type of self-explanation was analyzed by a two-way between groups MANOVA (diagrams, text) (Table 5). The only significant difference was for the goal-driven explanations ($F(1, 18) = 6.36$, MSE $= 8.46$, $p = .021$).

Pearson correlation coefficients were calculated for the number of self-explanations and students' scores on the pre-test and post-test by condition. There was a single significant effect. Students who produced more self-explanations in the diagram condition scored higher on the post-test ($r = .74$, $p < .05$).

3. Discussion

Participants given information about the human circulatory system in diagrams learnt more than those given text. At post-test, diagrams students included almost four more correct concepts in their blood path diagrams than they had at pre-test, compared to text students who included one extra correct concept. However, diagrams students were presented with this information directly whereas text students had to infer the relation between the textual description of blood flow and the body outline. Hence, to claim that diagrams differentially aid learning, it is important to examine performance on the other tasks. Explicit questions were presented as text or graphics so ensuring no simple compatibility of format between mode of learning and testing. At post-test, 80% of the answers diagram student gave were correct, compared to 56% of the answers of text students. Moreover, the implicit and knowledge inference questions were asked and answered in textual form. It could be argued that this advantages text learners. However, the diagram students performed better than the text students, particularly on the more difficult knowledge inference questions (78.3% for diagrams compared to 46.6% in the text).

We argued that diagrams would facilitate learning about the structure and function of the human circulatory system by promoting computational offloading, re-representation and graphical constraining. Furthermore, this study points to a new reason why diagrams may benefit learning; that they can promote the self-explanation effect. Students given diagrams generated significantly more self-explanations than students given text (whilst spending significantly less time learning and uttering fewer words), which in turn lead to more effective learning.

There are multiple differences between text and diagrams and these differences exist at many levels (i.e., cognitive, semantic and affective). It is corresponding likely that there are multiple reasons why studying diagrams may lead learners to generate more self-explanations. Furthermore, it is feasible that learners will be influenced by several factors simultaneously.

Firstly, diagrams reduce memory load and cognitive effort by computational offloading. Self-explaining is a challenging activity that many learners do not engage in spontaneously. Diagrams free the limited resources of learners to engage in meaning-making activities. Diagrams limit abstraction and aid processibilty by restricting the learners' interpretation of the situation (Stenning & Oberlander, 1995). For example, the sentence "Blood from the left ventricle flows through the left semilunar valve, into the aorta", does not make explicit the size and exact positions of these features, whereas the diagram does. If text learners are attempting to infer these features, they may have insufficient resources for self-explanation. Furthermore, the working memory model (Baddeley & Hitch, 1974) would suggest that self-explanations and written text are processed by the phonological loop, whereas diagrams are processed by the visual–spatial scratch pad. Learning can be made more effective by presenting information in two modalities so that processing is distributed over multiple systems (e.g., Mayer & Moreno, 2002). Thus, combining verbal self-explanations with graphical diagrams should maximize memory resources.

Secondly, diagrams encourage causal explanations either about a single diagram, "*blood flowing in here to the heart has then to be pumped to the lungs to be oxygenated*" or across multiple diagrams "*. . . an artery seems to be more muscular than a vein, because it carries blood with higher pressure . . . it has to carry it all the way to all the parts of the body . . .*". Diagram learners may create mental images (e.g., Kosslyn, 1994; Tabachneck-Schijf et al., 1997), which encourages them to integrate new information into this picture. Additionally, the specificity of graphical representations may promote casual explanations. Consider the sentence "Blood from the right ventricle flows through the semilunar valve into the pulmonary artery and then to the lungs". That the blood is deoxygenated must be inferred from other sentences. With the diagram (using red and blue for blood high in oxygen and carbon dioxide), it is impossible not to see that the pulmonary artery carries deoxygenated blood and leads to “blood flows through the pulmonary artery to the lungs to get oxygen”. Of course, “deoxygenated” could be added to the sentence, but including more specific information is easier with graphical representations.

There may be affective reasons for the greater number of self-explanations in the diagrams condition. Students indicated that the colorful diagrams were more interesting to learn with than the text. When material is made more interesting, students select more information for active processing (Mayer, 1993).

Although text students spoke significantly more than diagrams students, the majority of their statements were paraphrases and they gave fewer self-explanations. For example, a text learner stated “*The heart is divided in half by the septum*” and after prompting “*because it has different chambers and they need to be divided*”, whereas a typical diagrams self-explanation is “*The septum is like a wall because you need to separate the oxygenated from the deoxygenated blood*”. In addition, some text students developed visual analogies. For example, “... *blood travels like a river!... so the arteries are the river, and the ... arterioles are the tributaries*” and “... *this is like a pyramid ... we have a top-down system ... capillaries are third ...*”. This style of self-explaining was not positively associated with learning outcomes. This is in line with VanLehn and Jones’s (1993) account of the self-explanation effect, which suggests that analogies can encourage learners to bypass gaps in their knowledge.

3.1. Is self-explanation more beneficial when learning from diagrams or text?

Overall, there was a significant positive correlation between the number of self-explanations and post-test scores. However, when this was examined by format only diagrams students were found to have benefited from self-explaining. Renkl (1997) showed that learners who focused their explanations around principles and goals (principle-based explainers) or who anticipated steps in the solution of problems (anticipative reasoners) were most successful. In the diagrams condition, 70% of the self-explanations concerned goals and principles. Diagrams students generated significantly more goal-driven explanations and no self-explanations concerning principles were made by text students. In the text condition, 50% of explanations concerned goals and there was a correspondingly higher number of elaborative explanations. This may explain the lack of relationship between self-explanation and learning in the text condition.

That diagrams students differentially benefit from increased self-explaining confirms the predictions of Aleven and Koedinger (2002) who proposed that self-explanations are particularly beneficial when supporting integration of textual and graphical modes of expression. It also supports Cox’s views that diagrams provide salient feedback, which encourages learners to give self-explanations and that translating between modalities will be beneficial (Cox, 1999). It does not support Wilkins’s concern that diagrams will inhibit self-explanation effect. In this study, the diagrams were primarily pictorial with simpler format and operators than the more complex diagrams in her mechanics situations. Learners also reasoned with presented representations rather than constructing representations, and there are considerable differences between these activities (e.g., Cox & Brna, 1995). Consequently, this study does not contradict her hypothesis but illustrates the likely scope of its effect.

4. Conclusion

The results of this research adds to the growing body of evidence that shows that self-explaining is an effective metacognitive strategy and supplies a further reason why graphical representations can be beneficial for learning. Furthermore, as many of the preceding experiments gave students both text and diagrams, some of the facilitatory effects of self-explaining may be due to the presence of diagrams. However, it should be remembered that concepts that could not be represented without text were excluded from the study. Hence, this result does not sustain "graphical superlativism" but instead supports the argument that representations should match the structure of information required by the problem (Gilmore & Greene, 1984).

The current study did not explore exactly what features of diagrams promote the self-explanation effect and the students' self-explanations suggest that they were sensitive to many different features of the representations. This is unsurprising as there are multiple differences between text and diagrams. Further controlled studies manipulating diagram style and content more closely are required. Another question concerns whether the results were due to the way that diagrams promoted verbal explanations or whether they rest on the interrelation between different forms of representation. If students given text are encouraged to sketch explanatory pictures as a form of self-explanation will the same benefits accrue? Future research should determine if this result is best considered as a diagram or a multi-representational effect.

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