Why Sketching May Aid Learning from Science Texts:

Contrasting Sketching with Written Explanations

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Keywords: drawing; sketching; self-explanation; learning strategy; constructive learning; learning from text; comprehension

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Abstract

The goal of this study was to explore two accounts for why sketching during learning from text is helpful: 1) sketching acts like other constructive strategies such as self-explanation because it helps learners to identify relevant information and generate inferences; or 2) that in addition to these general effects, sketching has more specific benefits due to the pictorial representation that is constructed. Seventy-three seventh-graders (32 girls, *M* = 12.82 years) were first taught how to either create sketches or self-explain while studying science texts. During a subsequent learning phase, all students were asked to read an expository text about the greenhouse effect. Finally, they were asked to write down everything they remembered and then answer transfer questions. Strategy quality during learning was assessed as the number of key concepts that had either been sketched or mentioned in the self-explanations. The results showed that at an overall performance level there were only marginal group differences. However, a more in-depth analysis revealed that whereas no group differences emerged for students implementing either strategy poorly, the sketching group clearly outperformed the self-explanation group for students who applied the strategies with higher quality. Furthermore, higher sketching quality was strongly related to better learning outcomes. Thus, the study's results are more in line with the second account, sketching can have a beneficial effect on learning above and beyond generating written explanations; at least, if well deployed.

Keywords: drawing; sketching; self-explanation; learning strategy; strategy quality; visuo-spatial representation

Why Sketching May Aid Learning from Science Texts: Contrasting Sketching with Self-Explanations

1 Introduction

To learn complex material effectively, students must engage in meaningful processing of instructional content. In the educational literature, a variety of learning strategies have been proposed that aim to support meaningful processing, thereby enabling a deeper understanding of the content. In particular in science domains, it has been suggested that sketching serve as one such strategy (Ainsworth, Prain, & Tytler, 2011; van Meter & Firetto, 2013). In many science domains being able to construct an internal mental representation or mental model of visuo-spatial arrangements of objects is pivotal to deeper understanding. For instance, when attempting to learn about the functioning of a pulley system, it is important that a learner knows about how the pulleys are connected to each other via the rope that runs through them and how they are attached to the ceiling (Hegarty, 1992). Visuo-spatial arrangements like the pulley system can be described in text. However, verbal expressions describing spatial configurations such as object X is next to object Y are often ambiguous, incomplete, and implicit (Stenning & Oberlander, 1994). Thus, such expressions require further interpretation for a comprehensive understanding to be derived. As a consequence, constructing an accurate spatial mental model from verbal descriptions may be difficult for learners (Tversky, 1991). Asking learners to generate a sketch that represents the text that they are reading may help the learners to better understand the spatial relations described within the text. In particular, creating an external visuo-spatial representation from text forces learners to make explicit decisions regarding visuo-spatial aspects of a to-be-learnt content (e.g., about the size and relative position of objects, potential connections between them), thereby potentially yielding a more accurate spatial mental model.

In the present paper, we were interested in whether the need to generate a visuo-spatial representation based on linguistic input during sketching has an additional benefit that goes beyond elaborating the linguistic input only verbally and inferring novel aspects of information from it. To this end, we compared sketching to another strategy that is known to support learning from text, namely, self-explanation. For sketching and self-explanation, research has shown that learners are likely to differ in their ability to implement either strategy, which in turn will influence the strategies' effectiveness. We were thus also interested in whether the relative effectiveness of sketching and self-explanation would be moderated by the quality of strategy implementation.

1.1 Self-explanation when learning from text

Self-explanation refers to the process of generating explanations to oneself during learning from expository text or other external representations (Chi, 2000). In generating an explanation, learners apply their prior knowledge to information given in the text, infer novel aspects from it, and restructure their knowledge. Since the seminal study by Chi, Bassok, Lewis, Reimann, and Glaser, 1989) and its replication by Renkl (1997) research on self-explanation has a long-standing tradition in the field of learning and instruction. Learners who engage in self-explanations show higher learning outcomes than those who do not. Moreover, typically the more self-explanations they generate, the better their learning outcomes (Ainsworth & Loizou, 2003; Chi et al., 1989; Chi, De Leeuw, Chiu, & LaVancher, 1994; Pirolli & Recker, 1994; Renkl, 1997). In studies with students of the same age of the participants in our study Coté, Goldman and Saul (1998) found that paraphrasing can also support understanding of texts if supported by prior knowledge. In addition, research has shown that students can become better self-explainers by training them and prompting them to engage in self-explanations (Ainsworth & Burcham, 2007; Bielaczyc, Pirolli, & Brown, 1995; Chi et al., 1994; McNamara, 2004, in press; Schworm

& Renkl, 2007). In summary, explaining text is a very effective learning strategy that not only yields better learning outcomes when compared with other passive or physically active modes of learning, but also when compared with other forms of constructive learning activities where students engage mentally in the learning process to generate new knowledge (cf. for a recent review, Fonseca & Chi, 2011).

Despite the general effectiveness of self-explanation, it may be less beneficial when learning about phenomena that encompass many visuo-spatial aspects as is the case in many science domains. In particular, when generating a verbal explanation for themselves while reading expository text, students use the same modality for expression as the one in which the input was presented. Students may find it difficult to verbalize their understanding of visuo-spatial aspects described in the text because of the limitations that linguistic representations have regarding these aspects (Larkin & Simon, 1987). As a consequence, sketching may be better suited as a learning strategy in domains encompassing many visuo-spatial aspects.

1.2 Sketching when learning from text

While there is a long-standing tradition on research on the effects of self-explanations, the use of sketching as a learning strategy has only more recently come to prominence (see van Meter & Garner, 2005, for a review). When sketching whilst learning from expository text, students create a visuo-spatial representation for themselves based on the information given in that text. Evidence is accumulating that sketching can be an effective strategy when learning from text (e.g. Gobert & Clement, 1999; Leopold & Leutner, 2012; Schmeck, Mayer, Opfermann, Pfeiffer, & Leutner, 2014; Schwamborn, Mayer, Thillmann, Leopold, & Leutner, 2010; Van Meter, 2001; Van Meter, Aleksic, Schwartz, & Garner, 2006).

There are various reasons for why sketching may be an effective strategy for learning. According to what we call the general hypothesis, sketching may aid learning because like other learning strategies such as self-explaining it supports the identification of relevant information, deeper engagement with the learning material, and generation of inferences. According to this hypothesis, one would expect sketching to be equally effective as self-explanation. On the other hand, according to the specific hypothesis, the beneficial effects of sketching are additionally due to the fact that a visuo-spatial external representation is created. In particular, effects of sketching can be explained by referring to the process of creating a sketch as well as to the internal memory representation it is supposed to yield. Sketching forces learners to make explicit decisions regarding the representation of visuo-spatial information in the sketch (e.g., about the size and relative position of objects, potential connections between them) since per definition visualizations have a higher specificity with regard to these aspects (Stenning & Oberlander, 1994). Thus, learners are required to pay careful attention to visuo-spatial information stated in the text and to make inferences beyond the information given explicitly in the text in order to come up with a comprehensive sketch as a precise account of the phenomenon. Finally, in sketching they translate linguistic input into a visuo-spatial external representation rather than remaining within one representational format (Kozma & Russell, 1997). The effort associated with this translation process may yield better learning. With respect to the resulting internal representation, van Meter and Garner (2005) suggest that sketching will yield dual coding of information in memory (Paivio, 1991). That is, similar to learning from multimedia (i.e., externally provided combinations of text and pictures), during sketching a mental image is created in addition to the propositional representation derived from text; dual coding of information increases the likelihood of being able to retrieve the information from memory.

At present, the existing research does not allow discerning between the general and specific hypothesis to explain the effectiveness for sketching. In some of the studies students who sketched were compared with students who did not engage in any additional learning activities beyond reading the text (e.g., Schmeck et al., 2014; Schwamborn et al., 2010). In such a design the effects of sketching could be due to either general or specific effects. There are studies that have tried to overcome this issue by comparing sketching to main idea identification or summary writing (Leopold & Leutner, 2012; Leopold, Sumfleth, & Leutner, 2013). In these studies sketching still proved superior, suggesting that there may be more to sketching than what is induced by other verbal learning strategies. Other studies have compared sketching with externally provided visualizations. If there were no differences between these conditions then the sketching effect would be specific and due to fact that it yields an (external and internal) visuo-spatial representation – similar to learning with multimedia. Unfortunately, findings from these studies are mixed in that some reveal no differences between learner-generated drawings and external visualizations (Hall et al., 1997; Schwamborn, Thillmann, Opfermann, & Leutner, 2011), others show a benefit of drawing over provided visualizations (Mason, Lowe, & Tornatora, 2013), but also the reverse pattern (e.g., Leopold et al., 2013).

Thus, at present we do not know whether the positive effects of sketching are due to meaningful learning activities conducted irrespective of whether generating a pictorial representation is required or whether they are more specific. Another problem with generalizing across previously mentioned studies is that sketching has been interpreted widely and may not in fact involve the freehand generation of sketches. Researchers have considered that free-hand sketches may be too challenging for learners and so in some studies learners were provided with predefined visual objects that had to be selected from a menu bar and that were then arranged to create a sketch. Because these objects are external visual representations that already provide information regarding an element's visual appearance (e.g., its shape, size, etc.) this way of implementing a sketching-to-learn strategy is a hybrid approach somewhere between a generative learning strategy where students actively construct an external representation of the content and a multimedia condition.

To test whether sketching relies on the generation of an external visuo-spatial representation and to overcome some of the aforementioned issues, in the present study we compared students who were instructed to generate freehand sketches with students who were instructed to self-explain. If benefits of sketching are jointly due to general constructive processes and combined with its specific visuo-spatial nature, then sketching should outperform self-explanations for domains and tasks where visuo-spatial representations are helpful.

1.3 Quality of strategy implementation

The second aspect of the study concerned whether students can implement both the newly taught strategies in similar ways and whether the quality of implementation of either strategy affects and potentially moderates their effectiveness. Quality of strategy implementation has been discussed as a major factor influencing the effectiveness of both self-explanation and sketching.

In self-explanation research, strategy quality has typically been measured as the number of correct inferences (i.e., going beyond the provided information) created during the self-explanation (Chi, 2000). However, other studies have found that number of paraphrases is also positively associated with learning through explanation (e.g., Ainsworth & Burcham, 2007; Coté et al.,, 1998).

In sketching research, strategy quality has often been equated with the accuracy of the sketches relative to the information provided in the text or to an expert's representation (e.g., Schwamborn et al., 2010; Van Meter, 2001), that is, the degree to which the drawings represent the linguistic information in a comprehensive and correct fashion.

A positive relationship between strategy quality and strategy effectiveness has been established in at least two ways: First, studies have made use of the inter-individual variability in students' strategy quality and have analyzed the association between strategy quality and post-comprehension measures. For instance, Ainsworth and Loizou (2003) showed that a higher number of deep-quality self-explanations was related to better post-comprehension. Schwamborn et al. (2010) found strong positive correlations between students' sketching accuracy and their performance in various learning outcome measures. They refer to this finding as the prognostic drawing effect. Second, studies have introduced interventions aimed at improving strategy quality and tested their effects on learning outcomes. Similarly, these studies typically find positive effects of strategy interventions on students' learning (e.g., for self-explanations: Ainsworth & Burcham, 2007; Bielaczyc et al., 1995; Chi et al., 1994; McNamara, 2004, in press; for drawing: Van Meter, 2001; Van Meter et al., 2006).

An interesting question is whether self-explanation and sketching can be implemented with the same ease. Both strategies require cognitively demanding inferencing activities. However, sketching requires an additional cognitive process, namely, the transformation of a linear, descriptive linguistic representation into a non-linear, depictive representation. Accordingly, one might predict that young students only recently taught the strategy of sketching may struggle to implement it successfully. But, on the other hand, sketches may facilitate inferencing especially with respect to visuo-spatial information because they naturally require learners to express this information explicitly. Indirect evidence in favor of this explanation comes from a study by Ainsworth and Loizou (2003), where provided diagrams led students to generate more self-explanations than the equivalent text, suggesting that visual representations supported more inferencing activity.

Moreover, if there are differences regarding students' ability to self-explain or sketch, the question is how these ability differences affect the relative effectiveness of either strategy for learning. On the one hand, if learners implement both strategies poorly, then it is unlikely that there will be any differences between learning from self-explaining or sketching. On the other hand, differences are more likely to emerge, if learners implement both strategies in their best possible way.

1.4 Overview of study

In the present study, seventh graders were instructed to generate either written self-explanations or sketches while reading an expository text about the greenhouse effect. We assessed the quality of their strategy implementation during learning by determining the accuracy of the self-explanations and sketches as well as their learning outcomes by means of a recall and transfer test.

If the positive effects of sketching that have been observed in earlier studies were due to solely to the fact that sketching like other generative learning strategies promotes elaboration and inferences, then we would expect no differences in learning outcomes between the sketching and the self-explanation conditions. If, however, positive effects of sketching are due to the fact that learners have to create a visuo-spatial representation of what they have understood from reading the text, then we would expect the sketching group to outperform the self-explanation group given that the learning task requires understanding of visuo-spatial aspects.

In addition, we were interested in three aspects of strategy quality. First, we explored whether one of the strategies would be easier to apply (yielding a higher quality of strategy implementation). Second, based on previous research we expected strategy quality to predict learning outcomes. Third, is another unexplored question, namely, whether this association would be the same for self-explanation and sketching. It might well be that strategy quality is more important for one learning strategy than for the other one. If so, differences between learning outcomes in the experimental conditions will vary as a function of strategy quality. If both strategies are implemented poorly it is likely there would be no differences in outcomes.

However if both strategies are implemented well, then the learning strategy for which strategy quality is more strongly correlated with learning outcomes, should outperform the other learning strategy.

2 Method

2.1 Participants and Design

Participants were 74 seventh-graders from three different classrooms of a secondary education school in Germany. One student failed to fill in the posttest and was excluded from data analyses, leaving 73 students (M_{age} =12.82 years, SD = 0.48; 32 girls). Participation was voluntarily. For each student who took part the class received 10€. Participants within each class were randomly assigned to one of the experimental groups: sketching (n = 36) or self-explanation (n = 38).

2.2 Materials

We used three expository texts from introductory chemistry education containing no pictures. The text for modeling the strategy use was about the water cycle (247 words), while a text that explained how a sewage plant works (229 words) was used to practice the strategies. The text for the final learning episode, for which we assessed learning outcomes, dealt with the greenhouse effect (194 words). It described how sunbeams impinge upon the earth, are partially reflected by the atmosphere, how light beams change into heat, how heat radiation penetrates through the atmosphere into space, is partially reflected by the atmosphere back to the earth and how the greenhouse effect relates to carbon dioxide emitted through industry and cars. All of the topics required understanding of visuo-spatial information (e.g., the angle by which the heat radiation is partly reflected by the atmosphere). None of the three topics had been formally taught to the students before.

2.3 Strategy Instruction

In both conditions the experimenter first read the text on the water cycle aloud, than identified together with the participants the main ideas and highlighted them, summarized the main ideas with her own words, and integrated some prior knowledge. Depending on experimental condition the experimenter then explained and showed at the board either how to generate a self-explanation or how to make a sketch from the text. Participants in the self-explanation group were taught to explain the main aspects of the process they just learnt to themselves and to write down this explanation in a way that they would later be able to reconstruct this process. This included asking students to integrate their prior knowledge with the text in order to fill in gaps in their understanding. Participants in the sketching group were told to explain the main aspects of the process they just learnt to themselves and to generate a sketch for themselves that would help them to later reconstruct the process. The sketch did not have to be aesthetically pleasing. Then all participants practiced the learned strategy with the text on the sewage plant. They received a strategy reminder that consisted of a short summary of the strategy that they had learned earlier.

2.4 Measures

To control for students' basic understanding of Natural Sciences phenomena we used 15 items from the Scientific Literacy Test (SLT) by Laugksch and Spargo (1996) that addressed the topics of energy, climate, atmosphere, and eco systems since these were most closely related to the experimental task. In addition, because there were relatively few items referring to students' understanding of energy, which is, however, pivotal to the greenhouse effect, we augmented the items taken from the SLT with three further items (i.e., 'Energy can disappear'; 'Light, warmth, and motion are all forms of energy'; 'Energy can not be transferred'). Importantly, all items captured rather general conceptions that students have regarding the aforementioned topics, but not detailed knowledge on how the earth, its atmosphere, and the sun interact with regard to the greenhouse effect. For each correct answer participants received one point, yielding a maximum score of 18 points.

To test our assumptions regarding the role of strategy quality during learning, we needed to come up with a measure that assessed strategy quality for both learning strategies in comparable ways. To this end, we determined 20 major idea units contained in the text on the greenhouse effect. The explanatory text and the list of idea units is contained in the Appendix. Participants received one point for each major idea unit from the text that they correctly mentioned in their written explanations (self-explanation group) or that they correctly transformed into a visuo-spatial representation by sketching it (sketching group). Two raters scored 23% of data yielding an inter-rater agreement for strategy quality Krippendorff's alpha = .86, which was considered a good agreement. Hence, one of the raters scored the remaining data and her scores were used to determine the final score. Strategy quality was a continuous variable represented by the total number of correctly mentioned / drawn idea units, ranging from 0 (minimum quality) to 20 (maximum quality).

To assess learning outcomes, we used recall and transfer questions. The recall question asked students to write down everything that came to mind regarding the greenhouse effect. Participants received one point for each major idea unit that they recalled. We applied a more coarse-grained approach to scoring recall performance compared with the strategy quality by scoring only 12 units idea units rather than the 20 during learning. This decision was made prior to marking and acknowledged the fact that some of the very specific details from the text would be unlikely to be recalled from memory. Thus, the maximum recall score was 12 points. There were 4 open transfer questions (e.g., 'What would happen if the earth did not have an atmosphere?'). A marking rubric of correct answers and criteria for correctness was produced beforehand, yielding a maximum of 9 points. Two raters scored 23% of the data. Inter-rater agreement for recall was Krippendorff's alpha = .84, and for transfer .63. One rater scored the remaining data.

2.5 Procedure

The experiment took place in school. One week before the experiment the chemistry teacher administered the SLT. For the main part of the study, the participants were randomly assigned to different rooms in which one of the two conditions was ascertained by two experimenters. At each work station there was a booklet welcoming the participant a questionnaire with demographic questions, an explanation of the learning strategy, and three different texts with space reserved for applying the strategy. The texts were always available whilst self-explaining or sketching. The modeling of either strategy took about 20 minutes. Students then practiced the strategy for 20 minutes. After a short break the participants had 20 minutes to study the text on the greenhouse effect. They were instructed to proceed in the learning episode as previously taught but were given no further strategy information. Finally, the participants' learning outcomes were tested without access to the learning material or the sketches / self-explanations.

3. Results

To control for individual variability in students' scientific literacy, the SLT scores were used as a covariate in all analyses. Adjusted means and standard errors are reported in Table 1.

**** INSERT TABLE 1 ABOUT HERE ****

Students' ability to recall the text did not reliably differ between conditions as revealed by an ANCOVA, $F(1,70) = 3.17$, $MSE = 9.23$, $p = .08$, $\eta^2 = .04$. If anything, students in the sketching group tended to recall more concepts from the text than students in the self-explanation group. However, as can be seen in Figure 1 this effect was only true for some learners (i.e., those who showed a high level of strategy implementation), a finding that we will address in more detail below. There was no effect of experimental condition on students' transfer performance, $F < 1$. In both analyses, students' scientific literacy did not have any reliable impact (for transfer: $F < 1$; for recall: $F(1,70) = 1.76$, $MSE = 9.23$, $p = .19$, $\eta^2 = .03$).

**** INSERT FIGURE 1 ABOUT HERE ****

Regarding strategy quality, an ANCOVA revealed a marginal effect of condition, $F(1,70) = 3.61$, $MSE = 17.72$, $p = .06$, $\eta^2 = .05$, suggesting that students in the sketching group tended to transform more of the concepts mentioned in the text into a sketch than the self-explanation group mentioned in their written self-explanations. Overall, the strategy quality was relatively high in that 70.5 percent of the concepts mentioned in the text had been re-represented correctly (see Figure 2 for sample sketches). Students' scientific literacy was not associated with strategy quality ($F < 1$).

**** INSERT FIGURE 2 ABOUT HERE ****

To investigate whether strategy quality matters for both the effectiveness of self-explanations and of sketches, we determined the correlations between strategy quality and learning outcomes. Higher strategy quality was significantly related to better recall in the sketching condition ($r = .499$, $p < .01$), but not in the self-explanation condition ($r = .218$, $p > .10$). The correlations with transfer were not significant (self-explanation: $r = .201$; drawing: $r = .179$; both *p*s > .10).

The differential pattern of correlations between strategy quality and recall performance implies that differences between the two strategies in terms of learning outcomes become apparent only if the strategies have been implemented with a sufficient degree of quality. To test this assumption, we ran a regression analysis using students' recall performance as dependent variable and strategy quality, experimental condition, and the interaction between the two variables as predictors (controlled for scientific literacy). To follow up on significant interactions, simple slope analyses were conducted at -1 standard deviation (SD) and +1 SD relative to the mean of the continuous variable (Aiken, West, & Reno, 1991). Simple slope analyses estimate the size of an effect of condition at different points of the continuous variable (strategy quality). To determine the effect of condition for students with lower strategy quality, the effect is estimated at – 1 SD relative to the mean of the continuous variable, whereas for students with better strategy quality it is estimated at + 1 SD. Hence, this analysis allows estimating the size of the effect of experimental condition for students who implement strategies either poorly or rather well without having to divide the sample into two distinct groups by, for instance, a median split. Results from this analysis are illustrated in Figure 1, which shows recall performance as a function of strategy implementation in each of the two experimental conditions.

The overall regression model was significant, $R^2 = .21$, $F(4,68) = 4.61$, $p = .002$. Neither students' scientific literacy, *Beta* = 0.553, $\beta = .18$, $p = .10$, nor experimental condition served as significant predictors, *Beta* = 0.319, $\beta = .10$, $p = .36$. However, strategy quality was positively related to students' ability to recall information from the learning episode, *Beta* = 1.505, $\beta = .49$, $p = .001$, suggesting that those with higher quality of strategy implementation performed better in the recall test than did those with lower quality. Moreover, there was a significant interaction between experimental condition and strategy quality, *Beta* = 0.972, $\beta = .31$, $p = .02$. Simple slope analyses conducted at -1 SD and +1 SD of the continuous moderator strategy quality resolved this interaction as follows (Figure 1): For students who had implemented their strategy with low quality only (bars on the left) learning strategy did not matter, *Beta* = -0.636, β = -.21, p = .28. For students with a high strategy quality (bars on the right), on the other hand, sketching lead to better recall than self-explaining, *Beta* = 1.291, β = .42, p = .01.

Running the same analysis for transfer performance yielded a non-significant overall model, R^2 = .06, F(4,68) = 1.00, p = .41.

4. Discussion

The present study investigated whether sketching has a specific benefit for learning due to the fact that a visuo-spatial representation is created that goes beyond benefits that can also be observed from other learning strategies such as self-explaining. The results showed that an instruction to generate sketches whilst learning from text did not reliably show better recall of the text's main ideas than an instruction to self-explain. This stands in contrast with findings from previous studies (e.g., Leopold & Leutner, 2012; Schmeck et al., 2014; Schwamborn et al., 2010) that have found rather strong effects favoring sketching. However, in all of these studies students had to construct diagrams based on pre-defined visual elements, whereas we asked students to generate freehand drawings, which may be more challenging for them. Moreover, with the exception of the Leopold and Leutner study (2012) control conditions were used that did not instruct students to engage in other ways of meaningful learning. Both differences may explain why at an overall level we found no effects of sketching compared to the self-explanation group.

Instead, benefits of sketching were limited to those learners who are able to comprehensively and accurately represent in their drawings what is described in the text. That is, for learners who implemented either strategy with high fidelity (i.e., produced paraphrases or sketches for a large number of text idea units), sketching clearly let to higher recall than self-explaining. This was the case even though the recall test potentially favored the self-explanation group, for which the modality of the learning strategy and of the recall test was the same (i.e., both verbal). On the other hand, the sketching group first had to transform the linguistic input from the text into a visuo-spatial representation whilst learning and then again use the verbal modality for the recall test. The results suggest that at least those learners who were able to accomplish this translation between representations (Kozma & Russell, 1997) benefitted from generating a sketch above and beyond self-explaining. Thus, sketching effects seems to be specifically tied to the fact that learners create an external visuo-spatial representation and are not just due to generative learning activities more generally. What cannot be decided based on the present data is which cognitive processes cause this specific effect of sketching, that is, whether it is caused by dual coding of information (Paivio, 1991) or by the fact that sketching leads to an external representation that is more precise with regard to visuo-spatial information than a linguistic representation (Larkin & Simon, 1987; Stenning & Oberlander, 1994).

Students' sketches tended to contain more ideas from the text than did the self-explanations; however, the observed effect was rather weak. Thus, we refrain from interpreting this finding as this finding as suggesting that sketching may be easier to implement than self-explaining. Similar to other studies we found that sketching quality (i.e., the comprehensiveness of the sketch relative to a text) was highly predictive for learning (e.g., Schwamborn et al., 2010; Van Meter, 2001). This was not the case for the quality of self-explanations, which did not correlate with learning outcomes. It is yet unclear what causes individual differences regarding the quality of sketches. Previous studies have found no relation with students' prior knowledge or their spatial ability and strategy quality (Schmeck et al., 2014; Schwamborn et al., 2010). In the present study, there was no association between the comprehensiveness of students' sketches and scientific literacy, which can be considered a more generic aspect of prior knowledge. Further studies need to explore whether there are other learning characteristics that may explain why some students are well prepared or able to transform linguistic input into a visuo-spatial representation, whereas others fail. It could well be that students' spatial ability and/or spatial working-memory capacity plays a role in this transformation, in that learners with higher spatial abilities and/or working-memory capacity are better able to comprehend visuo-spatial verbal descriptions (cf. Pazzaglia & Cornoldi, 1999) and to express this information using a sketch.

There are some limitations of the present study that need to be acknowledged. First, in contrast to other studies we did not observe any effects of sketching on transfer performance. This may have to do with the set-up of our study. Students did not have any prior knowledge regarding the topic that would have helped them to go beyond what was stated explicitly in the text; also the text was very short, thereby providing little opportunity for inferences. The shortness of the learning phase may also explain why in general the effects of sketching were small compared with our studies, which found sketching effects at an overall level.

A related issue concerns the way we measured strategy quality across both learning activities, which was assessed as the number of idea units correctly written in the self-explanation group and drawn in the sketching condition. One might argue that a verbal statement can be considered a self-explanation only if it contains an inference (Chi, 2000); however, given the set-up of our study we expected to see little in depth inferencing activity. Moreover, there are studies showing that paraphrases are also linked to better learning (e.g., Ainsworth & Burcham, 2007; Coté et al., 1998). Nevertheless, the fact that there was no reliable correlation between explanation quality and learning outcomes may suggest that the measure did not fully assess cognitive activities that contributed to better learning in this condition. Moreover, the question remains whether our measure assessed the same thing for both learning strategies. Whereas for a verbal statement it can be determined quite easily if it is a paraphrase and not an inference, the situation becomes more complicated in sketching. Visuo-spatial information conveyed through text is often incomplete and implicit; creating a sketch forces learners to make explicit decisions regarding visuo-spatial aspects (e.g., about the size and relative position of objects). Thus, learners will always make albeit minimal inferences when transforming linguistic input into a sketch, even when this sketch is just considered representational, that is, “intended to depict what is described in the text” (Schmeck et al., 2014, p. 275). Further studies need to be conducted in which the material and population are more likely to result in paraphrases and inferences so that the role of these two aspects of strategy quality can be studied for both, self-explanation and sketching.

This also raises the more general point of what constitutes a high-quality sketch and how sketching quality relates to the domain of study. Students in the present study were instructed not to consider the artistic quality of their sketches but focus on the fact that the sketches were accurate representations of relevant information. The learning domain was one where understanding visuo-spatial information is likely to be crucial. Thus, we believe that sketching is mostly helpful in domains where understanding requires an accurate representation of how relevant objects look like and how they are related to each other in space. In contrast, there may be other learning domains, whose central aspects can be better expressed using words (e.g., an explanation of how a democracy works). As much as externally provided visualizations such as pictures or diagrams are more effective for learning when the content is visuo-spatial in nature, also the effects of generating a visualization during sketching are bound to the same precondition (cf. Larkin & Simon, 1987).

Our findings also imply that in order for sketching to be effective, sketches must be accurate and comprehensive. In the present study, low-quality sketches were unlikely to be due to a lack of effort that students put into producing the sketches. That is, there were many low-quality sketches like the one shown in Figure 2 that contained many elements, but that were inaccurate. We provided some instruction for students concerning what we hoped they would sketch and why they should do so. However, these instructions may only have been helpful for some students as there was clear variability in the drawings. It is as yet an open question what instructional methods might be most effective for teaching students how to generate higher-quality sketches.

Despite these limitations, the present study highlights the importance of strategy quality for sketching. Thus, from an educational perspective we need to gather more insights on why some learners produce comprehensive sketches and what we can do to help students to create them.

5. References

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Appendix

Explanatory text (translated from German)

The Greenhouse Effect

The greenhouse effect means a rise in temperature on our earth. It is caused by the emission and the production of various substances and gases, which lead to an enhanced thermal re-radiation from the atmosphere back to the earth.

The sun radiates light to the earth. Part of this radiation is reflected back as early as it reaches the outer atmospheric layer. The bulk of the solar radiation, however, makes it to the surface of the earth. There the solar radiation is converted into heat and reflected back. A certain percentage of this heat radiation gets through the atmosphere back into space. Another percentage of radiated heat naturally bounces off the atmosphere and is reflected back to the earth. This natural reflection ensures an average temperature of about 15 degrees Celsius on the earth. Without this reflection, the temperature would be -18 degrees.

But nowadays, there is an increased emission of gases such as carbon dioxide (CO_2) and the so-called "greenhouse gases". Those are emitted for example by cars and the industry. These gases accumulate in the atmosphere and have the effect that the thermal radiation cannot escape into space, but remains between the atmosphere and the surface of the earth. The logical implication is a worldwide increase in temperature.

Coding scheme for strategy quality. One credit was given whenever a concept or idea was either mentioned in the self-explanation or depicted in the drawing. In the self-explanation condition, concepts or ideas did not need to be mentioned verbatim, but any phrase with an identical meaning was coded as correct.

1. Sun (as source of light beams)
2. Light beams
3. (directed towards) earth
4. Splitting of light beams into two parts
5. One part: reflected at the atmosphere
6. Other part: Back into space
7. Bulk of the radiation

8. Reaches the earth
9. Is converted into heat
10. Reflected by the earth
11. Splitting of thermal radiation into two part
12. One part: Gets through the atmosphere into space
13. Other part: Another percentage is reflected by the atmosphere
14. average temperature of about 15 degrees
15. Emission of gases (CO_2)
16. (caused by) e.g. industry/cars
17. Accumulate in the atmosphere
18. Thermal radiation cannot escape into space
19. Heat remains
20. Increase in temperature