Comprehending process diagrams in biology education

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CHAPTER 6

DISCUSSION

In this thesis, we aimed at getting deeper insight into students' difficulties comprehending process diagrams. These insights were used to inform the design of an intervention. In this concluding chapter, we first present the main results of the four separate studies of this thesis and then some reflections upon the studies and directions for future research. Finally, implications for educational practice are presented.

1. MAIN RESULTS

In the first two studies (chapter 2 and 3), we focused on factors that influence students' difficulties with process-diagram problem solving tasks. Two levels of process-diagram problem solving tasks were defined: tasks with a low and tasks with a high cognitive demand. The first study showed that cognitive task demand predicted students' difficulties with process-diagram problem solving tasks. Furthermore, students have difficulties with diagrams that use unfamiliar component conventions and that have a small number of components. Process-diagram tasks with a high cognitive demand when the content of the diagram was new proved to be more difficult than tasks with a high cognitive demand when the diagram did not contain new information.

Difficulties with process-diagram problem solving tasks are also predicted by student characteristics, i.e., prior knowledge, spatial abilities and working memory capacity (study 2, chapter 3). Students' performance on tasks with a high and a low cognitive demand were positively related to prior knowledge. Furthermore, scores on a spatial ability test that measured the ability to search for information in a complex spatial field were related to tasks with a low cognitive demand. The latter result was as hypothesized because we expected tasks with a low cognitive demand to rely on searching and encoding the presented information. Mental visualization and rotation abilities (i.e., visualization and spatial orientation factors, Ekstrom et al., 1976) were, as hypothesized, not related (with exception of one of five tests for these factors) to tasks with a low or a high cognitive demand (cf. Wu & Shah, 2003, for Chemistry problem solving). Students' scores on a visual working memory test were positively related to tasks with a high cognitive demand. The latter result was expected because tasks with a high cognitive demand require the formation of an elaborate mental model in working memory.

In the third study (chapter 4), we focused on learning activities that distinguished more and less successful students while studying process diagrams. In line with previous research (Meijer, Veenman, & Van Hout-Wolters, 2006; Pressley, 2000; Pressley & Afflerbach, 1995), we distinguished between an orientation and a main phase. In the orientation phase, successful students more often used the legend and activated prior knowledge. In the main phase, successful students more often: 1) gave meaning to process arrows, 2) questioned themselves, and 3) read the organizational levels of the diagrams. Results from measuring eye-movements showed that successful students also spend more time in the main area of the process diagram and shifted their focus more between different areas of interest. Successful students used a more coherent approach of interrelated learning activities and employed learning activities consistently across learning tasks.

The fourth study showed that students' learning from process diagrams can be enhanced by an intervention. Multiple-strategy training had an indirect positive significant effect on the experimental group, through invested mental effort, on learning from process diagrams, compared to the control group.

2. REFLECTIONS AND DIRECTIONS FOR FUTURE RESEARCH

2.1 Reflection on theory

Students construct a mental model in working memory when they process an external representation. For this thesis, multimedia theories (Mayer, 2001; Schnotz & Bannert, 2003), theories that focus on learning from graphical representations (e.g., Hegarty, 2005), and cognitive load theory (Sweller, 1988; Sweller, 1994; Sweller, Van Merriënboer, & Paas, 1998) provided a framework on how students construct a mental model of an external representation, i.c., process diagram. The construction of a mental model depends on (the interaction of) design features of the external representation (e.g., Canham & Hegarty, 2010; Mayer & Gallini, 1990), cognitive processes (Hegarty, 2005; Kriz & Hegarty, 2007), and abilities (Hegarty & Sims, 1994; Mayer & Sims, 1994; Sweller et al., 1998). Mental model construction is also influenced by the task; different tasks lead to different mental models (Schnotz & Bannert, 2003; Winn, 1991). The present thesis benefitted from the afore-mentioned theories; they served as a base to get deeper insight into students' difficulties with process diagrams. Such a deeper insight was also needed for the design of the intervention study (study 4, chapter 5). For this intervention study we could not rely on previous research—different external representations have different cognitive demands (Ainsworth, 2006)—and a thorough investigation on students' difficulties with process diagrams had not been performed yet. This thesis adds to previous research by showing how students' difficulties with a specific type of external representations, i.c., process diagrams, depends on design features (e.g., number of components), cognitive processes (e.g., activating prior knowledge; using the legend), abilities (e.g., working memory capacity), and task (cognitive task demand).

Research on self-regulated learning (Boekaerts, 1997) and (meta)cognition (Veenman, 2012) also supported the present thesis. Self-regulated learning theory provided a framework for students' learning activities while studying process diagrams. We also based the intervention of the final study (study 4, chapter 5) on self-regulated learning by using the cognitive strategy instruction model by Harris and Graham (1996), i.e., a model developed for supporting students in writing. We demonstrated that the latter model can also be used to facilitate students' learning from an external representation, i.c., the process diagram. Previous research on meta(cognition) identified many activities students employ, e.g., studying text (e.g., Pressley & Afflerbach, 1995) or solving problems (Meijer, Veenman, & Van Hout-Wolters, 2006). This thesis benefitted from these studies and adds some distinct activities (e.g., using the legend of a process diagram in the orientation phase) that can be distinguished when students study process diagrams.

2.2 Definition and measurement issues

A reoccurring issue in the four studies of the present thesis concerns how we defined and measured variables. In this section, we will reflect on some of these issues, discuss the effect these issues might have had on the results, and suggest some directions for future research.

In the first two studies (chapter 2 and 3), we defined two levels of task demand: tasks with a low and high cognitive task demand. In the first study, inter-rater agreement was high ($\kappa = .87$). In the second study, task demand explained 30% variance of task difficulty and internal reliability of low (KR-20 = .85); high (KR-20 = .82) cognitive task demand indicated a well-defined construct. Although two levels of task demand were functional with regard to this thesis' research questions, a more elaborated categorization of process-diagram problem solving tasks might be useful and could help the Biology education community more. Teachers might, for instance, benefit from such a categorization as a tool for selecting and designing tasks for an exam. Studies that focus on using Bloom's Taxonomy (Bloom, Krathwohl, & Masia, 1956) in Biology might give guidance to such a categorization: Crowe, Dirks, and Wenderoth (2008) developed an instrument for classifying tasks for several biological topics; Quillin and Thomas (2015) developed an instrument for classifying drawing tasks within Biology.

In the first study (chapter 2), we obtained items from Dutch Biology national exams. An advantage was that we were able to work with a large dataset ($N = 42891$) and could select tasks from many items (704). A disadvantage was that we were not able to measure effects of student variables directly. Instead, we had to rely on inter-rater agreement by experts. Inter-rater agreement (Cohen's' κ) showed that these constructs were measured reliable; students' prior knowledge and familiarity with the components, arrows, and spatial arrangement of the process diagrams were .87, .86, .82, .87, respectively. Not measuring the latter variables directly meant that within cohort between students variance—cohort mean exam scores were used as the dependent variable—was not addressed. It is, however, clear that students' prior knowledge and familiarity with the components, arrows, and spatial arrangement, varies within cohorts. Future studies might consider a more fine-grained approach by directly measuring students' familiarity with the components, arrows, and spatial arrangement (prior knowledge is directly measured in the second study). Furthermore, contrary to our expectations, multiple regression analysis showed no significant effect (when controlled for other factors, e.g., cognitive task demand) for prior knowledge on task difficulty. We cannot rule out that not finding a significant effect might partly be due to not considering between student variance in prior knowledge.

In the second study (chapter 3), we measured students' prior knowledge on four secondary school Biology topics (ecology, protein synthesis, dissimilation, and hormones). All prior knowledge items (56) were aggregated into a single scale and internal reliability (KR-20 = .78) was confirmed. Tasks with low or high cognitive demand (KR-20 = .85, .82, respectively) were also based on the four topics and we assumed performance on these tasks to be invariant across topics. We examined whether prior knowledge scores were related to scores on tasks with low and high cognitive demand. This meant that we did not assume that there were between topic differences in the relation between tasks with a low and high cognitive demand and prior knowledge. We also did not assume that there were between topic differences in the relation between scores on tasks with a low and high cognitive demand and scores on the spatial ability and working memory tests. One could argue that the latter relations might vary per topic of the process diagram. For instance, the role of prior knowledge on task performance might be more distinct when the design features of process diagrams of a specific topic are more conceptual and abstract (see study 1, chapter 2) compared to other topics. Future studies might provide insight whether the relations examined in the second study vary per topic.

In the fourth study (chapter 5), we assessed with a pretest how much students comprehended of a process diagram they had just studied. The items (8) of the pretest did not converge into a single scale, i.e., internal homogeneity as indicated by KR-20 could not be confirmed. There might be several reasons for this. For instance, the pretest (and the posttest) assessed how much a student was able to comprehend from a process diagram. It is plausible different students focused on different aspects of the process diagram in the pretest and that this compromised internal homogeneity. Another possibility is that student's prior knowledge might be fragmented; knowing one item is not per se a precondition for knowing the other item. Learning the content of the process diagram of the pretest relied on basic prior knowledge of the topic (i.e., entero-hepatic cycle) and on prior knowledge about (biochemical) transformations and transport (e.g., diffusion, active and passive transport). When different students had different prior knowledge this might also have compromised internal homogeneity of the pretest. We must mention here that although the topics of the process diagrams of the pretest and posttest differed, we did not expect that this influenced internal validity. The topics of the process diagrams of the pretest and the posttest were both within the domain of biochemistry and relied mainly on (biochemical) transformations and transport processes. The latter processes were not instructed in the intervention phase; hence, the influence of prior knowledge was kept constant.

2.3 Ecological validity and generalization

All participants in all four studies were students who were part of the target group of the present thesis, i.e., pre-university upper secondary school students with an intermediate level of expertise in Biology. All tests were administered at students' school, e.g., in classroom, computer lab, exam room. In the first two studies, parts of the data were collected during a national exam (first study, chapter 2) and a regular school exam (second study, chapter 3). Furthermore, we used authentic tasks students regularly encounter in secondary Biology education. Process diagrams were carefully selected (e.g., from Biology textbooks used in higher education) and adjusted for the target group. Biology teachers advised us on many issues on a regular basis.

There might be some concerns about the generalizability of the second and third study because students are from two classes from a single school (but not the same two classes in both studies). However, the school is a regular secondary school in the Netherlands and we have no reasons to expect that our samples are not representative. Another issue with respect to generalization is this thesis' target group, i.c., pre-university upper secondary school students with an intermediate level of expertise in Biology. The results might be specific for students with their level of expertise and experience with learning and problem solving with process diagrams. For this, we recommend to be careful to extend the results to other target groups such as lower grade students and university students.

Furthermore, this thesis focused on a specific type of diagram, i.c., the process diagram. Process diagrams used in this thesis were from a single domain, i.c., Biology, but we used many different process diagrams with a variety of biological topics and design features. For this, we believe our findings extent to process diagrams from other domains (e.g., chemistry, physics, geography, etc.). However, results cannot be easily extended to other type of diagrams (e.g., tree diagrams, phase diagrams, Venn diagrams) because of substantial differences in design features.

A final remark can be made with respect to the generalizability of the research design of the intervention in the fourth study (chapter 5). Future intervention studies might also benefit from including possible mediating variables in their design (see also Zhao, Lynch, & Chen, 2010). As mentioned in the fourth study: "Including mediators shows which variables are influenced by the intervention and how these variables contribute to the expected effect" (p. 77).

2.4 Unit of analysis

In the third study, we identified learning activities that distinguished more and less successful students while studying process diagrams. We performed correlational analyses to examine how these learning activities are interrelated. Although the analysis offers insight into the coherence of students' approach while studying process diagrams, learning activities are not single events but belong to a string of activities that contain students' means and goals. Correlational analyses do not consider the order and the functional relationship of the learning activities. Future studies might consider an analysis that takes the order and the functional relationship of the learning activities into consideration, e.g., path analysis.

2.5 Consistency

In this section, we will discuss how the first three studies of this thesis have informed the final intervention study (study four, chapter 5). We will discuss which paths were followed and which were not and some suggestions for future research will be provided.

In the concluding section of the first study (chapter 2) we formulated three suggestions for the design of an intervention. One of the suggestions of the first study was followed-up in the final intervention study, i.e., the suggestion to "facilitate students in learning how to gain a deeper understanding of diagrams that contain new information". This suggestion was based on the finding that students have difficulties with tasks with high cognitive demand when the content is new. The other two suggestions of the first study had no follow-up in the present thesis. One suggestion was to teach students strategies for encoding diagrams with unfamiliar components and the other suggestion was to focus on problems solving with abstract process diagrams. The suggestion of the second study (chapter 3) to "design a training that focuses on solving tasks with high cognitive demand" was also not followed-up in the final intervention study of this thesis.

We did not include these suggestions for practical reasons and due to progressive insight. Including these suggestions would largely increase the size of the intervention. As mentioned in the final study, we were dedicated to develop a short training to provide teachers the opportunity to use the intervention in classroom. Furthermore, the intervention focused on *learning* from process diagrams and not on *problem solving*; the findings of the first two studies were related to students 'difficulties with process-diagram problem solving tasks. However, we assume that there is an overlap in activities students have to employ when *solving tasks* with a high cognitive demand and when *learning* from process diagrams. Tasks with a high cognitive demand are usually more global and, as in learning, students have to search, encode, integrate and infer (evaluate, compare, judge) the presented information (Hegarty, 2005). Hence, facilitating students *how* to learn from process diagrams might also help them to solve problems with process diagrams. Future studies might, however, incorporate the suggestions that were not followed-up in the final intervention of this thesis into the design of a training.

Furthermore, in the second study (chapter 3), we identified spatial ability factors that were related to process-diagram problem solving. In the concluding section of that chapter we suggested that learning strategies might be especially important for students with low spatial skills. This suggestion had no follow-up in the fourth study (chapter 5). The decision not to include spatial ability tests in the pretest phase of the fourth study was also based on a practical reason: administering spatial ability tests cost extra time that was not available. However, in future studies we recommend to include spatial factors as possible moderating factors for the effect of an intervention that facilitates students' understanding of process diagrams. Students with low spatial skills might benefit more from such an intervention: The intervention might learn them strategies that compensate for their low spatial skills.

Finally, the third study (chapter 4) is strongly connected to the fourth study (chapter 5). The third study identified learning activities that distinguished more and less successful students while studying process diagrams. We assumed that students would benefit from facilitating them to employ these learning activities. Therefore, we included these learning activities into the design of the intervention.

3. PRACTICAL IMPLICATIONS

This thesis presents a fined-grained analysis of students' difficulties comprehending process diagrams. We think this thesis might help stakeholders of the Biology education community (e.g., students, teachers, teacher educators, instructional designers) to make informed decisions with regard to process diagrams when they teach, select or design learning materials, design exams, etc.

First, teachers should be aware of students' difficulties when dealing with process diagrams. Process diagrams are important and abundantly present in Biology education and teachers should know that students do not become diagrammatically literate by just studying it. We argue that students need more support when they have to solve process-diagram problems, e.g., as a task in their textbook, or when they have to learn from a process diagram, e.g., from their textbook or during instruction. The present thesis identified several conditions (e.g., cognitive task demand, familiarity with the components) that influence students' difficulties; teachers should consider these conditions when their students have to learn or solve problems with process diagrams. Especially, we want to advise teachers to demonstrate (more often) how they learn or solve problems with process diagrams by acting as a model. Teachers could act as a model by thinking-aloud to demonstrate how and when they activate prior knowledge, make inferences, use meta-information (e.g., title and the legend), ask questions, etc.

Second, teachers should be aware that individual differences, e.g., in prior knowledge, spatial ability, working memory capacity, meta(cognitive) learning activities, between students—even within homogenous groups—have an effect on students when they have to comprehend process diagrams. Teachers could use these findings in classroom. For instance, teachers might activate students' prior knowledge before process diagrams are instructed or give extra support to students with lower abilities.

Finally, this thesis might be interesting for teacher educators and instructional designers. Teacher educators might inform prospective teachers about students' difficulties with process diagrams. Such a lesson might be a good starting point for introducing themes like (meta)cognitive strategies, observational learning, and self-regulated learning. Instructional designers might benefit from this thesis in various ways. It might help them by making more informed decisions when selecting or designing process diagrams (and adjacent tasks) for educational materials. Furthermore, we hope it helps them to design educational material with more attention to *how* to comprehend process diagrams. For instance, the educational material might include instructions and tasks that help students to develop a more strategic approach (see fourth study, chapter 5). Students could also benefit from tasks where they have to explain the content of a process diagram to each other. Observing, comparing, and evaluating task behaviour (i.e., observational learning) of peers has proven to be effective in the domain of writing (Braaksma, 2002; Raedts, Rijlaarsdam, Van Waes, & Daems, 2007).