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Kragten, M.

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AUTHOR INDEX

SUMMARY

Students in secondary Science education seem to have difficulties with comprehending diagrams. Process diagrams are an important type of representation in Biology for explaining processes like protein synthesis, compound cycles, etc. 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.

CHAPTER 1

In chapter 1, we define and describe process diagrams as a distinct type of diagram. Process diagrams are defined as representations of how systems function (e.g., photosynthesis) by abstractions in components and arrows and that contain information that is spatial, dynamic, and schematic in nature. Process diagram communicate information through the spatial organization of elements (e.g., components, arrows, labels), e.g., components in close proximity are more related. Arrows in a process diagram represent the dynamic functioning of a system, e.g., arrows might represent the amount of carbon flux per hour or biochemical reactions. Process diagrams are schematic in nature because they are simplified and symbolic representations of the real world.

Next, we present the aim and the research questions of this thesis. The aim of this thesis was to design an intervention that facilitates students' comprehending process diagrams. We designed three studies to examine students' difficulties with process diagrams. The general scheme was to study the interaction between three constituting elements: 1) the task, 2) the student, and 3) the diagram design. The first three studies provided insights that informed the design of the final intervention study. The research questions of this thesis are:

1) What is the relationship between features of the (1) task, (2) student, and (3) diagram, on the one hand, and difficulty of a diagram task, on the other hand?
2) What is the relationship between students' learning activities while studying various process diagrams, and their resulting comprehension of these diagrams?
3) What is the effect of a strategy training on learning from process diagrams.

The research questions are answered by four studies (chapter 2 to 5). The first research question is answered by two studies (chapter 2 and 3), the third study (chapter 4) answers the second research question and the fourth study (chapter 5) answers the third research question.

CHAPTER 2

In chapter 2, we focus on explanatory factors that predict students' difficulties with process diagrams. From 18 compulsory national Biology exams of secondary school

pre-university students all process diagram tasks (n = 64) were included in corpus. Features of the task, student, and diagram were related to the difficulty of that particular task, indicated by the cohort mean exam score. We defined two levels of cognitive task demand: tasks with a ‘low’ and tasks with a ‘high’ cognitive demand. Students’ prior knowledge and familiarity with the components, arrows, and spatial arrangement of the process diagrams were coded by two experts. Diagram features, e.g., arrow and component type, were also coded.

A hierarchical regression analysis showed main effects for (1) the cognitive task demand, (2) the familiarity of the components, and (3) the number of components in a diagram. The cognitive task demand explained most of the variance (30%) in task difficulty. The familiarity of the components was also related to task difficulty. Diagrams that contain ‘familiar’ components showed higher mean exam scores and were therefore seen as less difficult. The number of components was negatively related to the task difficulty: The more components in a diagram the less difficult a task was. Information in a diagram might become more concrete if more components, i.e., bits of information, are added.

We also observed interactions. Within the category of tasks with a high cognitive demand, tasks about a diagram of which students have low prior content knowledge were more difficult than tasks about a diagram of which students have high prior content knowledge. Tasks with a high cognitive demand about a diagram with familiar arrows were, surprisingly, more difficult than tasks with a high cognitive demand about a diagram with unfamiliar arrows. This latter finding might be attributed to compensation for task difficulty by the large number of components in the diagrams involved.

The final model explained 46 percent of the variance in exam scores. The results of this study suggest that students have difficulties (1) with tasks that require a deeper understanding when the content is new, (2) with diagrams that use unfamiliar component conventions, and (3) with diagrams that have a small number of components and are therefore probably more abstract.

CHAPTER 3

In chapter 3, we focus on students’ ability to solve process-diagram problems in Biology and the relationship with prior knowledge, spatial ability and working memory. For this purpose, we developed a test that represents process diagrams and adjacent tasks used in secondary education Biology. We included a total of 28 process diagrams on four biological topics, i.e., ecology, protein synthesis, dissimilation, and hormones. The process-diagram test consists of 97 tasks. Each topic of the process-diagram test contains tasks with a low cognitive demand and a high cognitive demand. Students’ prior knowledge about the topics in the process-diagram test was measured by a test with 56 open and closed questions. Spatial ability and working memory tests were selected from the Ekstroms’ kit of factor referenced cognitive tests (Ekstrom et al., 1976).

As hypothesized, scores on the prior knowledge test correlated positively with scores on tasks with a low and a high cognitive demand. We expected that prior knowledge would be related with tasks with a low cognitive demand because prior knowledge facilitates search (Winn, 1993) and with tasks with a high cognitive demand because knowledge schemata keep cognitive load low (Sweller, Van Merriënboer, & Paas, 1998).

Scores on a test that measured the ability to search for information in a complex spatial diagram were also, as hypothesized, positively correlated with scores on tasks with a low cognitive demand. 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. This was expected because we assumed that process-diagram tasks do not require rotation or actually visualizing the movement of components.

Students' scores on a visual working memory test were, as hypothesized, positively related to tasks with a high cognitive demand. For tasks with a high cognitive demand, students need to build and explore an elaborate mental model that draws on the capacity of visuospatial working memory (Sims & Hegarty, 1997).

We conclude that the ability to solve process-diagrams problems involves the presence of prior knowledge, distinct spatial abilities, and visuospatial working memory capacity.

CHAPTER 4

In chapter 4, we examined students' learning activities while studying process diagrams, related to their resulting comprehension of these diagrams. Each student completed three learning tasks. Eye-tracking data was collected for all learning tasks: Verbal data was collected for the first two learning task by cued retrospective think-aloud protocol. Verbal data and eye-tracking data were collected as indications of students' learning activities. Students' comprehension was directly inferred from the verbal data from the first two learning tasks; comprehension of the third learning task was measured by a test.

For the verbal data, we applied a fine-grained coding scheme to optimally describe students' learning activities. The coding scheme distinguishes between an orientation phase and an elaboration phase. We defined three main categories of activities, i.e., cognitive, metacognitive and diagram learning activities. For the eye-tracking data, we used fixation time and transitions between areas of interest in the process diagrams as indices of learning activities.

Various learning activities were found that distinguished more and less successful students while studying process diagrams. Some distinct findings were that successful students were more likely to employ learning activities such as using the legend in the orientation phase; in the elaboration phase successful students more often give meaning to process arrows—80% between-student variance in comprehension score was predicted by the latter variable—and read the organizational levels. We also found that successful students were more likely to employ learning activities such as activating prior knowledge and self-questioning, and that they spend more time in the main area of the process diagram. Spending more time in the main area of the process diagram predicted 65% between-student variance in comprehension score.

We also analyzed between-student and within-student between-diagram differences in behavior and comprehension score across learning tasks. Students employed successful learning activities consistently across learning tasks. Furthermore, compared to unsuccessful students, successful students used a more coherent approach of interrelated learning activities for comprehending a process diagrams.

CHAPTER 5

In chapter 5, we evaluated the effect of multiple-strategy training on learning from process diagrams. The training focused on a stepwise working-routine that included when and where to employ cognitive and metacognitive learning strategies and on affective strategies to invest effort in the implementation of this stepwise working-routine.

The study followed an experimental pretest-posttest design. Students (N = 180) were randomly assigned to the experimental or the control condition. A computer-based multimedia learning environment was designed to deliver the instructions for the pretest, intervention, and posttest phase. This multimedia environment was designed following the general guidelines for the design of multimedia instructional material (Mayer & Moreno, 2002). The pretest, intervention, and posttest were conducted in one single session in a classroom with computers in students' school.

The pretest phase consisted of a learning task followed by a test. The learning task was to "understand as much as you can" from a process diagram. When students finished studying the diagram, they had to rate their invested mental effort and perceived task difficulty before they could start with the pretest. The pretest contained eight multiple-choice items that tested students' comprehension of the process diagrams.

Students in the experimental condition were presented a multiple-strategy training based on cognitive strategy instruction (e.g., Harris & Graham, 1996). The training consisted of five phases: 1) emphasizing that diagrams are important and useful, 2) explaining the strategic approach, 3) providing a model of the strategic approach, 4) practicing with the strategic approach, and 5) providing feedback on practicing.

The posttest phase, like the pretest phase, consisted of a learning task followed by a test. Again, students first had to rate their invested mental effort and perceived task difficulty before they could start with the posttest.

Structured equation modeling was applied to examine the direct and indirect effects, through invested mental effort and perceived task difficulty, on learning from process diagrams. We observed an indirect positive significant effect of multiple-strategy training, through invested mental effort, on learning from process diagrams compared to the control group. The latter result might suggest that students in the experiment group were willing to invest more mental effort because of increased strategy belief (Boekaerts, 1997). We observed no significant direct effect of multiple-strategy training on learning from process diagrams in the experiment group, compared to the control group.

CHAPTER 6

In the 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.

We reflect on theories that supported this thesis. 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 et al., 1998) provided a framework on how students construct a mental model of an external representation, i.c., process diagram. Furthermore, research on self-regulated learning (Boekaerts, 1997) and (meta)cognition (Veenman, 2012) also supported the present thesis. We argue that the present thesis benefitted from the afore-mentioned theories; they served as a base to get deeper insight into students' difficulties with process diagrams. This thesis adds to previous research a detailed analysis of students' difficulties with a specific type of external representations, i.c., process diagrams.

Furthermore, we reflect on issues that concern how variables were defined and measured, ecological validity and generalization. We also discuss how the first three studies of this thesis have informed the final intervention study.

Finally some practical recommendations are presented. 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. We argue that students need more support when they have to comprehend process diagram. This thesis identified several conditions that teachers should consider when their students have to learn or solve problems with process diagrams. Teacher educators might inform prospective teachers about students' difficulties with process diagrams. Furthermore, this thesis might help instructional designers by making more informed decisions when selecting or designing process diagrams (and adjacent tasks and instructions) for educational materials.

SUMMARY (DUTCH)

Studenten hebben moeilijkheden met het begrijpen van diagrammen. Procesdiagrammen vertegenwoordigen een belangrijk type diagram in de biologie voor het beschrijven van processen zoals eiwitsynthese, kringlopen, etc. Het doel van dit proefschrift was om dieper inzicht te krijgen in de moeilijkheden die studenten ervaren met het begrijpen van procesdiagrammen. Deze inzichten zijn gebruikt voor het ontwerpen van een interventie.

HOOFDSTUK 1

In het eerste hoofdstuk worden procesdiagrammen als een specifiek type diagram gedefinieerd en beschreven. Procesdiagrammen zijn gedefinieerd als representaties van hoe een systeem werkt door middel van abstracties in componenten en pijlen. Tevens communiceren procesdiagrammen ruimtelijke, dynamische en schematische informatie. Procesdiagrammen geven ruimtelijke informatie weer door de organisatie van de elementen (e.g., componenten, pijlen, labels), e.g., elementen die dichtbij elkaar staan, zijn nauwer met elkaar verbonden. Pijlen representeren het dynamisch functioneren van een systeem, e.g., pijlen die de hoeveelheid koolstofstroom per uur of biochemische reacties weergeven. Procesdiagrammen zijn schematisch omdat ze een vereenvoudigde en symbolische weergave van de werkelijkheid zijn.

Vervolgens beschrijven we het doel en de onderzoeksvragen van dit proefschrift. Het doel van dit proefschrift was om een interventie te ontwerpen die studenten ondersteunt bij het begrijpen van procesdiagrammen. We hebben drie studies ontworpen om de problemen die studenten hebben met het begrijpen van procesdiagrammen in kaart te brengen. Deze studies richten zich op de interactie tussen 1) de taak, 2) de student, en 3) het ontwerp van het diagram. Deze studies gaven inzicht in de moelijkheden die studenten hebben en gaven input voor het ontwerp van de uiteindelijke interventiestudie. De onderzoeksvragen van dit proefschrift zijn:

1) Wat is de relatie tussen de eigenschappen van de (1) taak, (2) student, en (3) diagram, enerzijds, en de moeilijkheid van een diagramtaak, anderzijds?
2) Wat is de relatie tussen de leeractiviteiten van studenten bij het bestuderen van een procesdiagram en de hieraan gerelateerde begripsvorming van dit diagram?
3) Wat is het effect van een training in strategieën op het leren van procesdiagrammen?

De onderzoeksvragen worden in vier studies beantwoord (hoofdstuk 2 t/m 5). De eerste twee studies (hoofdstuk 2 en 3) beantwoorden de eerste onderzoeksvraag, de derde studie (hoofdstuk 4) beantwoordt de tweede onderzoeksvraag en de vierde studie (hoofdstuk 5) beantwoordt de derde onderzoeksvraag.

HOOFDSTUK 2

In hoofdstuk 2 onderzoeken we factoren die moeilijkheden van leerlingen met procesdiagrammen verklaren. Het onderzoeksmateriaal bestond uit achttien centrale examens Biologie vwo. Uit deze examens zijn alle taken meegenomen die een interpretatie van een procesdiagram (n = 64) vereisen. Eigenschappen van de taak, leerling en diagram werden gerelateerd aan de moeilijkheidsgraad van de diagramtaak (d.i. 1 - de gemiddelde cohortscore). We definieerden twee niveaus van cognitieve taakbelasting: taken met een 'hoge' en taken met een 'lage' cognitieve belasting. De veronderstelde voorkennis van studenten en hun bekendheid met componenten, pijlen en de ruimtelijke rangschikking van de procesdiagrammen zijn gecodeerd door experts. Eigenschappen van het diagram, e.g., type pijl en component, zijn ook gecodeerd.

Een hiërarchische regressieanalyse toonde aan dat (1) de cognitieve taakbelasting, (2) de bekendheid met de componenten en (3) het aantal componenten in een diagram verschillen verklaarden in leerlingscores. De cognitieve taakbelasting verklaarde de meeste variantie (30%) van de moeilijkheidsgraad van de diagramtaak. De bekendheid met de componenten droeg ook bij aan de verklaring van de moeilijkheidsgraad. Diagrammen met 'bekende' componenten werden als minder moeilijk ervaren. Ook het aantal componenten droeg bij aan de moeilijkheidsgraad van de diagramtaak: Hoe meer componenten hoe eenvoudiger de taak. Dit effect zou verklaard kunnen worden doordat de informatie in een diagram meer concreet wordt als er meer informatiedelen aan worden toegevoegd: Het diagram wordt minder ambigue en de kans op foutieve interpretatie wordt kleiner.

Verder werden er interactie-effecten gevonden van de cognitieve taakbelasting met eigenschappen van de leerling en het diagram. Post-hoc analyse van de interactie tussen cognitieve taakbelasting en voorkennis toonde een significant verschil aan in de moeilijkheidsgraad van de diagramtaken bij een 'hoge' cognitieve taakbelasting en de mate van aanwezige inhoudelijke voorkennis. Post-hoc analyse van de interactie tussen cognitieve taakbelasting en bekendheid met de pijlen liet een negatief effect zien op de moeilijkheidsgraad van de diagramtaak bij taken met een 'hoge' cognitieve belasting wanneer de pijlen 'onbekend' zijn. Dit effect lijkt op het eerste gezicht een beetje vreemd maar een nadere analyse laat zien dat twee van de drie diagrammen met een 'onbekende' pijlen veel meer componenten dan gemiddeld bevatten. Deze toename in de concreetheid door de grote hoeveelheid componenten zou mogelijk kunnen compenseren voor het effect van 'onbekende' pijlen.

Het definitieve regressiemodel verklaarde 46 procent van de variantie in de examenscores. De resultaten van deze studie suggereren dat studenten moeilijkheden hebben (1) met taken die een dieper inzicht vragen wanneer de inhoud nieuw is, (2) met diagrammen die onbekende componenten bevatten, en (3) met diagrammen met een klein aantal componenten waardoor ze waarschijnlijk meer abstract zijn.

HOOFDSTUK 3

In hoofdstuk 3 meten we de bekwaamheid van studenten ten aanzien van het oplossen van problemen met procesdiagrammen in het biologieonderwijs en de relatie met voorkennis, ruimtelijke vaardigheden en werkgeheugen. We hebben een test ontwikkeld met 28 procesdiagrammen over vier biologische onderwerpen, i.e., ecologie, eiwitsynthese, dissimilatie en hormonen. De test bestaat uit 97 taken. Elk onderwerp uit de test bevat taken met een 'lage' en 'hoge' cognitieve belasting. De voorkennis van de studenten is gemeten door middel van een test met 56 open en gesloten vragen. Testen voor ruimtelijke vaardigheden en werkgeheugen zijn afkomstig uit *Ekstrom's kit of referenced cognitive tests* (Ekstrom et al., 1976).

Scores op de voorkennistest correleren positief, zoals verwacht, met scores op taken met een 'lage' en 'hoge' cognitieve belasting. We hadden verwacht dat scores op de voorkennistest zouden correleren met scores op taken met een 'lage' cognitieve belasting omdat voorkennis de zoekopdracht vergemakkelijkt (Winn, 1993); voorkennis vergemakkelijkt taken met een 'hoge' cognitieve belasting omdat de aanwezigheid van kennisschema's de cognitieve belasting laag houden (Sweller, 1988; Sweller, 1994; Sweller, Van Merriënboer, & Paas, 1998). Scores op een test die de bekwaamheid meet om informatie te zoeken in een complex diagram (Ekstrom et al., 1976) waren, zoals verwacht, ook positief gecorreleerd met scores op taken met een 'lage' cognitieve belasting.

Scores op testen die visualisatie en ruimtelijke oriëntatie meten waren, zoals verwacht, niet gerelateerd (met uitzondering van één van de vijf testen) met taken met een 'lage' en 'hoge' cognitieve belasting. Dit was verwacht omdat we aannamen dat procesdiagramtaken geen rotatie en visualisatie vereisen. Scores op een test voor ruimtelijk werkgeheugen waren, zoals verwacht, positief gerelateerd met taken met een 'hoge' cognitieve belasting. Voor taken met een 'hoge' cognitieve belasting moeten studenten een uitgebreid mentaal model construeren en onderzoeken en dit vereist capaciteit van het visueel-ruimtelijk geheugen (Sims & Hegarty, 1997).

We concluderen dat de bekwaamheid van studenten ten aanzien van het oplossen van problemen met procesdiagrammen gerelateerd is aan de aanwezigheid van voorkennis, specifieke ruimtelijke vaardigheden, en capaciteit van het visueel-ruimtelijk geheugen.

HOOFDSTUK 4

In hoofdstuk 4 onderzoeken we de leeractiviteiten van studenten tijdens het bestuderen van procesdiagrammen en hun begripsvorming van dit diagram. Elke student maakte drie leertaken. We verzamelden eye-tracking data tijdens alle leertaken én verbale data tijdens de eerste twee leeractiviteiten door middel van het *cued retrospective* hardop-denk protocol. Eye-tracking data en verbale data werden verzameld als indicatoren voor de leeractiviteiten van de studenten. De begripsvorming van het procesdiagram werd direct afgeleid van de verbale data voor de eerste twee leertaken; begripsvorming van het procesdiagram van de derde leertaak werd gemeten met een posttest.

De verbale data zijn geanalyseerd met een fijnmazig codeerschema om de leeractiviteiten van student te beschrijven. In het codeerschema onderscheiden we een oriëntatie- en een uitwerkingsfase. We definieerden drie hoofdcategorieën voor activiteiten, i.e., cognitieve, metacognitieve en diagram leeractiviteiten. De eye-tracking data zijn gebruikt voor het berekenen van de tijdsduur van de fixaties en transities tussen *areas of interest* als indicatoren van leeractiviteiten van studenten. Er zijn verschillende leeractiviteiten gevonden die succesvolle studenten vaker ontplooiden tijdens het bestuderen van procesdiagrammen. Enkele duidelijke verschillen waren dat meer succesvolle studenten vaker leeractiviteiten in de oriëntatiefase ontplooiden zoals de legenda gebruiken; in de uitwerkingsfase gaven meer succesvolle studenten vaker betekenis aan de pijlen van het procesdiagram—deze variabele verklaarde 80% van de variantie op de score van begripsvorming tussen studenten—en las deze groep studenten vaker de labels met de organisatieniveaus. We vonden ook dat meer succesvolle studenten vaker leeractiviteiten ontplooiden zoals het activeren van voorkennis en het zichzelf vragen stellen en dat ze meer tijd besteedden aan het kijken naar het gedeelte van het diagram waar het proces wordt weergegeven. Laatstgenoemde variabele verklaarde 65% van de variantie op de score van resulterend begrip tussen studenten.

We hebben ook de *between-student* en de *within-student between-diagram* verschillen in gedrag en resulterend begrip geanalyseerd. Studenten ontplooiden de leeractiviteiten consistent over leertaken. Verder gebruikten succesvolle studenten, vergeleken met minder succesvolle studenten, een meer coherente aanpak van samenhangende leeractiviteiten voor het begrijpen van procesdiagrammen.

HOOFDSTUK 5

In hoofdstuk 5 evalueren we het effect van een training met meerdere strategieën voor leren van procesdiagrammen. De training bevat een stapsgewijze werkwijze en bevat aanwijzingen waar en wanneer cognitieve en metacognitieve leerstrategieën ontplooid moeten worden. Tevens bevat de training affectieve strategieën om de studenten te stimuleren om inspanning te besteden aan het implementeren van deze stapsgewijze werkwijze.

De studie heeft een experimenteel pretest-posttest design. Studenten (N = 180) werden willekeurig toegewezen aan de experimentele- of de controleconditie. De instructies voor de pretest-, interventie-, en posttestfase werden geleverd door een digitaal multimedia leeromgeving. Deze multimedia leeromgeving was ontwikkeld volgens de richtlijnen voor het ontwerpen van multimedia-instructiemateriaal (Mayer & Moreno, 2002). De pretest, interventie en de posttest werden uitgevoerd in een enkele sessie in een computerlokaal op de school van de studenten.

De pretestfase bestond uit een leertaak gevolgd door een test. De leertaak was om ‘zoveel mogelijk te begrijpen’ van een procesdiagram. Wanneer studenten klaar waren met het bestuderen van het diagram dan moesten ze aangeven hoeveel mentale inspanning ze hadden verricht en hoe moeilijk ze de taak vonden. Vervolgens konden de studenten beginnen met de pretest.

De posttest bestond uit acht meerkeuzevragen en testte hoeveel studenten van het procesdiagram begrepen hadden. De studenten in de experimentele conditie kregen een training aangeboden met meerdere strategieën gebaseerd op het model van cognitieve strategie instructie (e.g., Harris & Graham, 1996). De training bestaat uit vijf fasen: 1) benadrukken dat diagrammen belangrijk en nuttig zijn, 2) uitleg van de strategische aanpak, 3) strategische aanpak demonstreren met behulp van een model, 4) oefenen met de strategische aanpak en 5) terugkoppeling op het oefenen.

De posttestfase bestond, net als de pretestfase, uit een leertaak en een test. Wederom moesten de studenten, wanneer ze klaar waren met het bestuderen van het diagram, aangeven hoeveel mentale inspanning ze hadden verricht en hoe moeilijk ze de taak vonden. Vervolgens konden de studenten beginnen met de posttest.

Met behulp van een *structured equation model* zijn de directe en indirecte effecten, door mentale inspanning en ervaren moeilijkheid van de taak, op leren van een procesdiagram onderzocht. We zagen bij de experimentgroep, vergeleken met de controlegroep, een indirect positief significant effect, door mentale inspanning, op leren van een procesdiagram. Laatstgenoemde zou kunnen suggereren dat studenten in de experimentgroep bereid waren om meer mentale inspanning te leveren omdat ze overtuigd waren van de strategie (Boekaerts, 1997). We zagen geen direct effect van de training op het leren van procesdiagrammen bij de experimentgroep, vergeleken met de controlegroep.

HOOFDSTUK 6

In het afsluitende hoofdstuk presenteren we eerst de belangrijkste resultaten van de vier afzonderlijke studies in dit proefschrift, vervolgens enkele reflecties op de studies en richtingen voor toekomstig onderzoek. Ten slotte worden de gevolgen van dit proefschrift voor de onderwijspraktijk besproken.

We reflecteren op studies die dit proefschrift ondersteunen. Theorieën over multimedialeren (Mayer, 2001; Schnotz & Bannert, 2003), theorieën die zich richten op het leren met grafische representaties (e.g., Hegarty, 2005), en de *cognitive load* theorie (Sweller, 1988; Sweller, 1994; Sweller, et al., 1998) dienden als raamwerk voor hoe studenten een mentaal model construeren van een externe representatie, i.c., een procesdiagram. Verder wordt dit proefschrift ondersteund door onderzoek dat zich richt op zelfgereguleerd leren (Boekaerts, 1997) en (meta)cognitie (Veenman, 2012). We beweren dat dit proefschrift heeft geprofiteerd van de voorgenoemde theorieën; ze dienden als een basis om dieper inzicht te krijgen in de moeilijkheden die studenten hebben met procesdiagrammen. Dit proefschrift voegt aan de bestaande kennis toe, een gedetailleerde analyse van de problemen die studenten ervaren met een specifiek type representatie, i.c., het procesdiagram.

Verder reflecteren we op kwesties die betrekking hebben het definiëren en meten van de variabelen, ecologische validiteit en generalisatie. We bespreken ook hoe de eerste drie studies van dit proefschrift hebben bijgedragen aan het ontwerp van de interventiestudie.

Ten slotte bespreken we enkele praktische aanbevelingen. We denken dat dit proefschrift de belanghebbenden van de biologie-onderwijsgemeenschap (e.g., studenten, leraren, onderwijsontwikkelaars) kan ondersteunen bij het maken van meer gefundeerde beslissingen wanneer ze lesgeven, leermateriaal selecteren of ontwikkelen, examens maken, etc. We beweren dat studenten meer ondersteuning nodig hebben bij het begrijpen van procesdiagrammen. Dit proefschrift heeft een aantal voorwaarden vastgesteld die leraren in overweging kunnen nemen wanneer hun studenten moeilijkheden ondervinden met het begrijpen van procesdiagrammen. Lerarenopleiders zouden toekomstige leraren op de hoogte moeten stellen van de problemen die studenten hebben met procesdiagrammen. Verder ondersteunt dit proefschrift onderwijsontwikkelaars om beter gefundeerde beslissingen te maken wanneer ze procesdiagrammen (en aanverwante taken en instructie) selecteren of ontwerpen voor onderwijsmateriaal.

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