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Students' Learning Activities While Studying Biological Process Diagrams

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Process diagrams describe how a system functions (e.g. photosynthesis) and are an important type of representation in Biology education. In the present study, we examined students' learning activities while studying process diagrams, related to their resulting comprehension of these diagrams. Each student completed three learning tasks. Verbal data and eye-tracking data were collected as indications of students' learning activities. For the verbal data, we applied a fine-grained coding scheme to optimally describe students' 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 while studying process diagrams were found that distinguished between more and less successful students. Results showed that between-student variance in comprehension score was highly predicted by meaning making of the process arrows (80%) and fixation time in the main area (65%). 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 process diagrams.

Keywords: *Process diagram; Learning activity; Comprehension; Eye tracking; Think aloud*

Introduction

Graphical representations are becoming increasingly prominent as carriers of meaning (Bezemer & Kress, 2008; Roth & McGinn, 1998). In current science textbooks, diagrams are more and more becoming instructional entities that can be studied, to some

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degree, independently from the text (e.g. Reece et al., 2010). Process diagrams are important and abundantly present in the diagram category. They describe how a system functions (e.g. photosynthesis, biogeochemical cycles) through the use of components that are connected by arrows. These arrows indicate transformation, movement, sequence, and so on. (Heiser & Tversky, 2006). Several studies demonstrate that students have difficulties interpreting such diagrams (e.g. Chittleborough & Treagust, 2008; Kriz & Hegarty, 2007; Schönborn, Anderson, & Grayson, 2002). Hence, a fine-grained analysis of learning activities that contribute to the diagram comprehension process can support the design of an evidence-based training program to foster learning from such diagrams.

Two popular process-tracing techniques to obtain an online record of students' learning activities are the think-aloud protocol (e.g. concurrent, Ericsson & Simon, 1993; cued retrospective, Van Gog, Paas, Merriënboer, & Witte, 2005) and eye tracking (Holmqvist et al., 2011).

Learning Activities

Learning is an active process of knowledge construction; students build an internal mental model to comprehend a diagram's content by employing learning activities, for example, encoding, inference (Hegarty, 2005). When students study diagrams autonomously, they must regulate the occurrence of these learning activities. They must employ cognitive as well as metacognitive learning activities and use conceptual and procedural domain knowledge to achieve learning goals (Boekaerts, 1997).

Cognitive learning activities. Various studies have described cognitive (and metacognitive) learning activities students used while studying texts (Pressley, 2000; Pressley & Afflerbach, 1995) and texts with diagrams (Azevedo & Cromley, 2004; Butcher, 2006; Cromley, Snyder-Hogan, & Luciw-Dubas, 2010). Cromley et al. (2010) collected verbal protocols from first year biology majors reading an eight-page passage from their textbook which included seven diagrams. A wide range of cognitive learning activities were distinguished, including activating prior knowledge, paraphrasing, summarizing, and inference. The authors examined whether students employed different cognitive learning activities when studying diagrams vs. full text. They found that when studying diagrams, the students made more inferences than in texts. Two variables were positively related to scores that indicated the elaborateness of the mental model: (1) the variety of the three types of inferences (i.e. inferences, elaborations, and hypotheses) and (2) the greater use of inferences. The latter finding is in line with many other studies reporting inferencing as crucial for the comprehension of graphical representations (Chi, 2000; Cromley et al., 2010; Hegarty, 2005; Kriz & Hegarty, 2007).

Metacognitive learning activities. Metacognitive learning activities regulate the cognitive learning activities. They are powerful predictors of general academic achievement

(Wang, Haertel, & Walberg, 1990) and science achievement (e.g. Akyol, Sungur, & Tekkaya, 2010). Meijer, Veenman and Van Hout-Wolters (2006) set up a taxonomy of metacognitive learning activities for the interpretation of think-aloud protocols of secondary school students. This taxonomy was constructed for analyzing protocols of students studying History texts and solving Physics problems. The taxonomy contains six main categories: orientating, planning, executing, monitoring, evaluating, and elaboration. Science reading research shows that proficient readers engage in orienting activities like reading the title and subheadings and planning activities concerning decisions about how to navigate through the instructional material (Pressley, 2000; Pressley & Afflerbach, 1995; Veenman, 2012). Furthermore, proficient readers reread difficult or important parts and they generate and answer questions (Veenman, 2012).

Domain knowledge. The importance of domain knowledge for the interpretation of scientific graphical representations is well documented (Canham & Hegarty, 2010; Cook, 2006; Cook, Carter, & Wiebe, 2008; Kriz & Hegarty, 2007). For instance, Kriz and Hegarty (2007) evaluated learning from animated displays (i.e. a flushing cistern). They found that participants with high domain knowledge (i.e. engineering students with no specific prior knowledge about how the flushing cistern worked) were more likely to construct a correct mental model (with correctness indicated by reported number of steps in the causal chain of the flushing cistern mechanism) than participants with low specific domain knowledge (i.e. humanities and social studies students). Interestingly, a majority of the students with high domain knowledge initially constructed an incorrect mental model. However, in contrast to the participants with low domain knowledge, these students were able to revise their mental models (with correctness indicated by correct answers on comprehension questions).

Learning Activities and Eye Movements

The eye–mind hypothesis claims a direct relationship between fixation durations and ongoing cognitive processes, where longer fixation durations indicate more extensive processing (Just & Carpenter, 1976; She & Chen, 2009). A crucial and difficult step in eye-tracking data is to determine which learning activities take place during eye movements. For instance, transitions (i.e. shifting focus from one location to another) could refer to either active integration of several parts of the representation (Mason, Pluchino, & Tornatora, 2013; Schwonke, Berthold & Renkl, 2009) or random ineffective searching behavior. Furthermore, students' attention might shift to specific parts of a representation due to prior knowledge or by an effect induced by the display (Canham & Hegarty, 2010; Kriz & Hegarty, 2007).

The influence of prior knowledge on eye movements has been examined within several domains. Cook et al. (2008) collected eye-tracking data to examine how prior knowledge influenced students' eye movements and interpretation of a graphical representation of cellular transport mechanisms. They found that low prior knowledge students tended to focus on more salient features (e.g. colored proteins), whereas high prior knowledge students tended to focus on more thematically relevant content.

Van Gog, Paas, and Van Merriënboer (2005) examined differences in eye movements between high and low expertise participants while performing a troubleshooting task about an electrical circuit. The level of expertise was indicated by a combined score of task performance, self-reported mental effort, and standardized mean score of total fixation time. Three phases of the troubleshooting task were defined: (1) problem orientation, (2) problem formulation and action decision, and (3) action evaluation and next action decision. They found that participants with high expertise spent relatively more time on the orientation phase and on evaluating their actions and deciding on their next action than participants with low expertise.

Several studies examined the relationship between eye-tracking measures, for example, fixation durations and transitions, and learning outcomes of scientific graphical representations (with or without explanatory text). Mason et al. (2013) examined how students learn from a science text in two conditions: with concrete or abstract illustrations. These researchers related a variety of eye-tracking measures to immediate and delayed post-tests on factual knowledge and on transfer. Most significant positive correlations were found for both post-tests on factual knowledge in the condition with abstract illustrations. Positive eye-movement variables were, among others, fixation duration on the illustration, first-pass fixation duration on the illustration and transitions from the end text segment to the illustration. They concluded that for the text with the abstract illustration, the quality of the learning performance is associated with higher fixation duration and more attempts to integrate the graphical and verbal information.

Schwonke et al. (2009) presented their participants worked-out examples of probability problems that included multiple representations, that is, a diagram, text, and an equation area. Participants had to relate and integrate these representations to build an elaborate mental model of probability theory. The researchers correlated eye movement measures (mean fixation time, cumulative fixation duration, mean fixation duration, and transition frequency) with participants' conceptual understanding and transfer performance. No relations with transfer performance were found. However, conceptual understanding correlated significantly with the mean and cumulative fixation duration on the diagram.

Focus and Rationale of the Present Study

In the present study, we aim to provide an *in-depth* analysis of which learning activities significantly predict students' comprehension level while studying a specific type of graphical representation, that is, the process diagram. Learning from graphical representations has been the interest of research for the last few decades in various fields, for instance, in contributions to multimedia theory (e.g. Mayer, 2001), cognitive load theory (e.g. Carlson, Chandler, & Sweller, 2003), and the role of prior knowledge and inferences (e.g. Canham & Hegarty, 2010; Cook, 2006; Cook et al., 2008; Kriz & Hegarty, 2007; Schwonke et al., 2009). Some diagram types, such as mechanical diagrams (e.g. Hegarty & Just, 1993; Kriz & Hegarty, 2007) or evolutionary diagrams (e.g. Catley, Novick, & Shade, 2010) have been studied extensively. However, research on *process diagrams* is limited. Körner (2005) demonstrated that students benefit from specific training on a specific graphical representation, that is, the hierarchical graph. A fine-grained analysis of how the more successful students learn from process diagrams might facilitate the design of a specific training for this diagram type.

Research Questions

The present study has two perspectives: (1) we monitored students' learning activities while they successively studied *three different* process diagrams and (2) we examined learning activities by triangulating eye-tracking and verbal data. The first perspective will give us an overview of learning activities that students employed while studying process diagrams. This will allow a detailed and robust analysis of which learning activities significantly predict students' level of comprehension of process diagrams. Such an analysis will enable us to determine whether these activities can be regarded as indicators of a more general strategic approach. The analysis of a *series* of tasks per student will enable us to determine whether students employed learning activities consistently across tasks.

The second perspective will serve three purposes. First, using alternative methods for assessing learning activities can validate these methods. Second, using two alternative methods might allow us to identify learning activities that otherwise would remain undetected. Third, relating eye-tracking and verbal data can tell us whether and to what extent relatively easy-to-collect eye-tracking data can indicate the occurrence of learning activities. This might be informative for researchers who are interested in obtaining eye-tracking data as an alternative for verbal reports as the latter are very labor intensive to analyze.

The following research questions were defined:

1. Which learning activities distinguish between relatively more and less successful students studying process diagrams? We answer this question by examining which learning activities are employed and when, after which we relate the frequency of these learning activities to the level of comprehension. Furthermore, we will examine whether students employed these significant learning activities consistently across tasks.
2. Are learning activities that significantly predict the comprehension of process diagrams related?

Method

Participants

Forty-two students from two classes in a regular secondary school in the northwest of the Netherlands were invited to participate in the study. A total of 32 students volunteered: 10 students declined the invitation mainly because they were not able to schedule an appointment due to other commitments during the data collection period. The students were finishing their last year of pre-university upper secondary education. They had chosen Biology as a major topic within their exam program with a study load of 480 hours during three years of upper secondary education. The students were in high-performing classes with a focus on Science, that is, all students had also chosen Chemistry and Math and most had also chosen Physics; they are likely to pursue an academic career. Finally, after the calibration procedure (see Section 'Eye-Tracking Apparatus and Materials'), we had to exclude three data sets. So 29 students (14 female, $M_{age} = 18.3$ years, age range: 17–19 years) participated in the present study.

Procedure for Learning Tasks

Three learning tasks were conducted consecutively in a quiet room during a single session of approximately one hour with each individual participant. The students were first acquainted with the cued retrospective think-aloud procedure (Van Gog, Paas, & Merriënboer, 2005)—which followed the first two learning tasks—by a warm-up session with a small process diagram. The students were then allowed to ask questions about the procedure; the experimenter could provide some guidance. The learning tasks, conducted by the first author (i.e. the experimenter), were then given to the students while their eye movements were monitored.

The first learning task started after the calibration procedure (see Section 'Apparatus and Materials') proved successful. The students received the following instruction:

> You will be presented with a process diagram. Try to understand as much as you can. The maximum time allowed is 4 minutes. If you are ready sooner you can stop by pressing the left mouse button.

Next, the students had access to the process diagram. Half the students started with diagram 1 (Figure 1(a)), the other half with diagram 2 (Figure 1(b)). When students completed this learning task, the instruction for the cued retrospective think-aloud procedure followed:

> You will be presented with an animation of where you were looking while you were learning from the diagram. Try to tell as much as you can about what you were thinking. Tell anything that comes to mind, act like you are alone and nobody is listening and keep talking. The animation will be played at half speed and you can pause and continue whenever you like.

Next, students were shown a replay of their eye movements using a spotlight. The animation ran at 0.5× normal speed. Students could pause and continue the animation whenever necessary by pressing the space bar. The procedure of the first learning task was repeated for the second learning task; when student were presented diagram 2 in the first learning task, they were presented diagram 1 in the second learning task and vice versa.

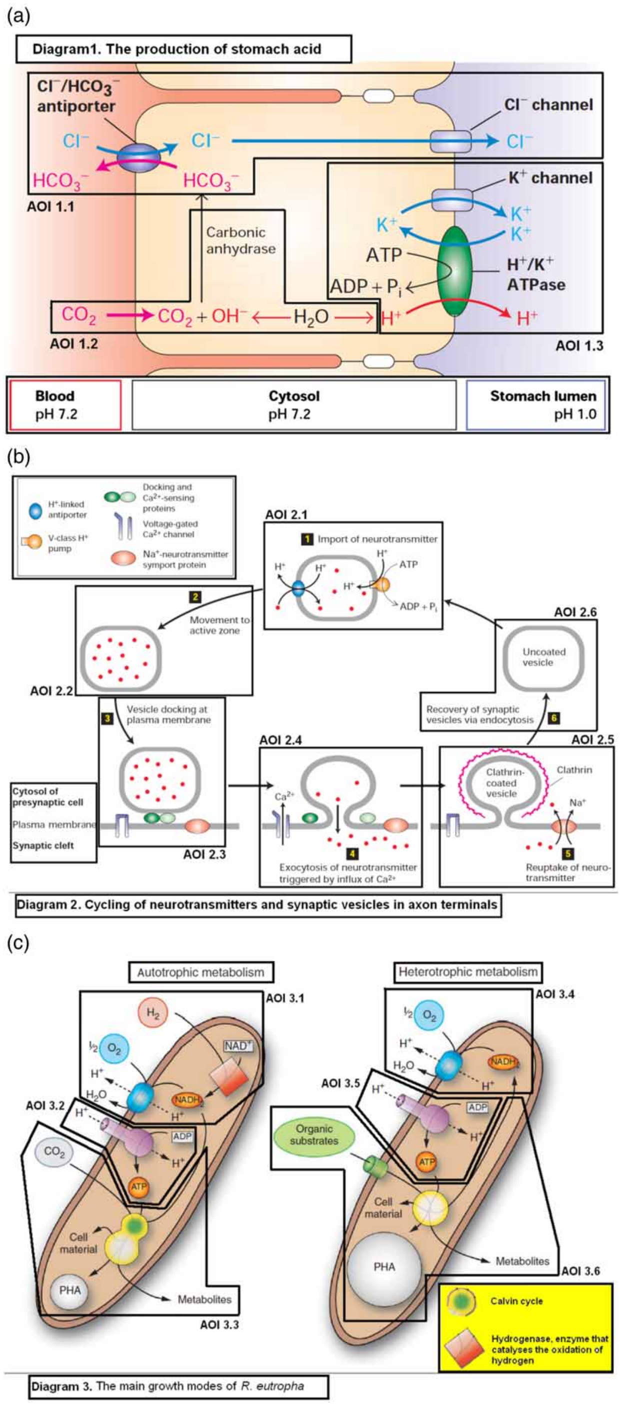

Figure 1. Three process diagrams used for the learning tasks. Diagrams used in the study were translated to Dutch. AOIs are indicated by thick black lines. The 15 AOIs of the main area are numbered, that is, diagram 1 (1.1 till 1.3), diagram 2 (2.1 till 2.6), and diagram 3 (3.1 till 3.6)

In the third learning task, students were presented with diagram 3 (Figure 1(c)) and were again instructed to try to learn as much as they could from this diagram. In addition, we informed them they had to complete a test about what they have learned from diagram 3; No think-aloud protocol was collected.

In sum, we collected eye-tracking data for three learning tasks and verbal data for the first two of them. Students' comprehension was directly inferred from the verbal data from learning task 1 and learning task 2; comprehension of learning task 3 was measured by a test (see Section 'Measuring Comprehension').

Selection of Process Diagrams

In this study, we focus on *learning* processes. Therefore, the topics of the diagrams were new and not part of the past curriculum. Diagrams 1 and 2 were slightly adjusted versions of diagrams from an international textbook for university students (Lodish et al., 2012). Diagram 3 was an adjusted version of a diagram from a scientific journal (Pohlmann et al., 2006). The process diagrams (Figure 1) were graphical representations with few verbal elements, for example, a title, a legend, and labels; there was no support from explanatory text. The diagrams were translated into Dutch. Students were not familiar with the processes presented in the diagrams but should have enough skills and knowledge to be able to comprehend the content; this was confirmed by their Biology teacher. With regard to diagram 1, students were taught in previous years about transport mechanisms (e.g. active and passive transport) and the composition of stomach acid (i.e. hydrogen chloride). But they were not taught how these processes relate to the process of the production of stomach acid. Concerning diagram 2, students were taught in previous years about how neurons work, but not about the cyclic process of regaining the neurotransmitters and the synaptic vesicle. As to diagram 3, students were taught in previous years about biochemical processes like assimilation and dissimilation, but not with hydrogen as an energy source or within bacteria that switch between metabolic modes.

Learning Activities from Verbal Reports

We established a coding scheme (Table 1) for the cued retrospective think-aloud protocols by continuously switching between a theoretical and data-driven point of view. We started with a broad range of previously defined learning activities from studies that focused on learning from text and diagrams (e.g. Azevedo & Cromley, 2004; Butcher, 2006; Cromley et al., 2010; Meijer et al., 2006; Van Gog, Paas, & Merriënboer, 2005).

The final coding scheme distinguishes between an orientation phase and an elaboration phase. We defined three main categories of activities, that is, *cognitive*, *metacognitive* and *diagram learning activities*.

The orientation phase contains all activities that occur before a student starts actually studying the main area (i.e. the numbered areas of interest (AOIs) in Figure 1) of the process diagram. Within this orientation phase, we found both *diagram learning*

Table 1. Coding scheme for the cued retrospective think aloud protocols and descriptive statistics

Phase → *Category* → Learning activity → 'Example'	Short term	M_s (SD) Learning task 1	M_s (SD) Learning task 2
Orientation phase			
Cognitive learning activities			
Activating prior knowledge	Orientate Prior	0.11 (0.31)	0.14 (0.35)
'and when I was reading stomach acid I thought of Chemistry and H_3O^+ etc.'			
Diagram learning activities			
Reading the title	Orientate Title	0.79 (0.42)	0.28 (0.45)
'I read the title, the production of stomach acid'			
Reading the labels regarding the organizational level	Orientate Level	0.50 (0.51)	0.07 (0.26)
'blood, cytosol and stomach'			
Localizing legend items in the main area			
'H^+ linked antiporter, where is it in the diagram, oh there at the first step'	Orientate Legend	–	1.66 (1.86)
Main phase			
Cognitive learning activities			
Giving meaning to a process arrow	Meaning Arrow	8.14 (3.32)	5.69 (3.47)
'H^+ is transported to the stomach'			
Inference	Inference	2.04 (1.95)	2.34 (2.00)
'ATP is used to transport H^+ to the stomach'			
Relating prior knowledge	Relate Prior	0.64 (0.87)	0.48 (0.95)
'that is active transport because ATP is being used'			
Alternative hypothesis	Alt. Hypothesis	0.75 (0.89)	1.76 (2.53)
'Chloride en Calcium Carbonate are being exchanged because otherwise the cell gets charged'			
Comparing elements across AOIs	Compare	0.68 (0.98)	1.07 (1.13)
'I'm checking what goes from the blood to the cytosol, what goes to the stomach and back to the blood'			
Metacognitive learning activities			
Self-questioning	Self-Questioning	3.61 (3.51)	1.93 (2.19)

(*Continued*)

Table 1. Continued

		M_s (SD)	
Phase → *Category* → Learning activity → ‘Example’	Short term	Learning task 1	Learning task 2
‘but why is ATP used? Is that for H^+ of K^+’			
Rereading parts of the diagram	Meta Reread	1.64 (1.10)	1.10 (0.98)
‘now I’m going to check everything for the second time’			
Diagram learning activities			
Reading the title	Read Title	0.64 (0.73)	0.48 (0.57)
‘so now I’m checking the title’			
Reading the labels regarding the organizational level	Read Level	1.36 (1.28)	1.07 (0.70)
‘the pH of the blood and cytosol is 7.2, the pH of the stomach is 1.0’			
Using the legend	Use Legend	–	3.10 (2.23)
‘Clathrin, I don’t know what it is so I look in the legend’			

Note: M_s = Mean number of utterances per student.

activities and *cognitive learning activities*. The category *diagram learning activities* in this phase contains activities using diagrams meta-information such as *reading the title*, *reading the labels regarding the level of organization,* and *localizing the legend items in the main area*. The category *cognitive learning activities* in this orientation phase deal with the activation of prior knowledge (Meijer et al., 2006).

The main phase begins when students started describing the process as depicted in the main area. The category *cognitive learning activities* within this phase contains five activities: (1) *giving meaning to a process arrow* (cf paraphrases, Butcher, 2006; descriptive statements, Lowe, 1999; paraphrasing, Meijer et al., 2006), (2) *inference* (cf integration inference, Butcher, 2006; knowledge inference, Chi, 2000; inference, Cromley et al., 2010; causal statements, Lowe, 1999), (3) *relating prior knowledge* (cf background knowledge, Cromley et al., 2010), (4) *alternative hypothesis* (cf hypothesizing, Azevedo & Cromley, 2004; Meijer et al., 2006), and (5) *comparing elements across AOIs* (cf connecting parts of text by reasoning, Meijer et al., 2006). *Giving meaning to a process arrow* is defined as correctly describing movement, transformation, or a next step in the diagram as depicted by arrows (Kragten, Admiraal, & Rijlaarsdam, 2013). Inferences are, as mentioned in the theoretical framework, essential for learning. We defined inferences as statements that include the relation between processes that are not literally displayed (cf Chi, 2000).

Students might use basic prior knowledge to facilitate learning from the process diagram. *Relating prior knowledge* defines connections students' made to background knowledge without integrating this into a causal statement. This means that students recognized a part of the process. Some students compared elements across AOIs. We interpreted this as an attempt to construct a global representation (Hegarty & Just, 1993) and coded it as *comparing elements across AOIs*.

The category *metacognitive learning activities* in the main phase contains (1) *rereading parts of the diagram* (cf rereads text in diagrams, Cromley et al., 2010; rereading, Meijer et al., 2006), and (2) *self-questioning* (cf Azevedo & Cromley, 2004; Cromley et al., 2010). We interpreted *self-questioning* as a metacognitive learning activity and not as a cognitive learning activity (cf Cromley et al., 2010), while students seemed to come up with questions when they are in cognitive disequilibrium. This suggests that students were monitoring their understanding. Initially, there were more subcategories within the main category *metacognitive learning activities* (e.g. evaluation of knowledge). However, the number of observations in these subcategories remained very small and did not show any significant relation with comprehension. For parsimony reasons, we did not include these items in the present study.

The category *diagram learning activities* contains the same items as the orientation phase.

Eye-Tracking Apparatus and Materials

Eye movements were captured using a custom-built corneal reflection binocular eye tracker. The eye-tracking software, that is, ITU Gaze Tracker 2.1b, ran on a dual core 2.5 GHz HP Pavilion laptop with a sampling rate of 60 Hz. The stimulus monitor (i.e. a 22″ screen with a resolution of 1920 × 1080) was connected through a VGA cable with the laptop; an external microphone and keyboard were also connected. This setup enabled the experimenter to perform the necessary actions during the sessions, for example, starting the calibration procedure, updating the database with eye-tracking data, and starting the measurements. The students sat in front of the screen with the position of their head fixed at 60 cm distance by a forehead rest. Calibration was performed before the start of the learning tasks by displaying nine white circles that shrank to a smaller circle on a black background. The calibration procedure was considered successful when the residuals for both eyes were <0.5° of the visual angle. The learning tasks were designed using OGAMA 4.2, that is, an open source software project which also supports capturing eye-tracking data send from ITU Gaze Tracker via UDP. Only fixations that lasted 100 milliseconds (or longer) within a 30 pixels diameter were analyzed.

Learning Activities from Eye-Tracking Data

Several AOIs were defined for each diagram according a functional criterion, that is, the AOIs enclose more or less different sub-processes of the entire process depicted in the diagram (Figure 1). Therefore, the sizes of the AOIs in the main areas varied. The title, legend (diagrams 2 and 3 only), and the level of organization, were also defined as AOIs. We assume that fixation time in the AOIs indicated ongoing learning activities; transitions between the AOIs indicated integration activities (Table 2).

Measuring Comprehension

For the first and second learning tasks, we inferred the level of comprehension of the depicted process directly from the inferences students made in their verbal reports. The rationale for not using an additional test is that the students interacted twice with the diagrams; in the learning phase and during the cued retrospective think-aloud protocols. Verbalizing their thoughts might have helped students to strengthen their understanding and this might endanger the validity of an additional test. Students' score on *inference* was calculated as the sum of the unique number of inferences uttered per learning task.

For the third learning task—after which no verbal data were collected—the students completed a comprehension test. The test consisted of reconstructing the processes of the two main growth modes (i.e. autotrophic and heterotrophic) of *E. eutrophia* by drawing. Asking students to reconstruct a biological process by drawing is commonly used to measure students' understanding of a specific topic (e.g. Quillin & Thomas, 2015; She & Chen, 2009). We did not expect students to use a memorization strategy as they were instructed to 'understand as much as they can' and they were not informed before the learning task on the type of test they had to perform.

The comprehension test had 28 items ($M = 13.0$; $SD = 7.0$; 1 = correct; 0 = incorrect); internal reliability indicated by KR-20 was 0.90. Items consisted of the combination of a component and the associated arrow leading away from the component in

Table 2. Description of eye-tracking measures

Eye-tracking measures	Explanation	*M* (SD) Learning task 1	Learning task 2	Learning task 3[a]
Fixation Time Main	Total time spent (s) in the AOIs of the main area	100.30 (40.45)	91.38 (36.37)	158.61 (62.03)
Fixation Time Title	Total time spent in (s) the AOI where the title is located	2.36 (1.22)	3.91 (3.80)	6.80 (4.95)
Fixation Time Level	Total time spent (s) in the AOI where the level of organization is located	8.37 (4.82)	6.01 (3.95)	7.55 (4.99)
Fixation Time Legend	Total time spent (s) in the AOI where the legend is located	[b]	23.77 (12.30)	9.18 (5.82)
Transitions Main	Number of transitions between AOIs of the main area	42.86 (20.66)	43.86 (21.67)	115.24 (46.43)
Transitions Title	Number of transitions from the main area to the AOI where the title is located	2.03 (1.50)	1.41 (1.35)	2.03 (1.59)
Transitions Level	Number of transitions from the main area to the AOI where the level of organization is located	11.14 (6.84)	8.45 (7.63)	7.45 (5.44)
Transitions Legend	Number of transitions from the main area to the AOI where the legend is located	[b]	19.97 (10.24)	13.28 (7.62)

[a]Maximum time in learning task 3 was 5 minutes, that is, 1 minute more than in the other two learning task.

[b]Diagram 1 contains no legend.

the right direction. Two completed examples of a part of the test are presented in Figure 2. Note that the students had to reconstruct the autotrophic *and* the heterotrophic mode; Figure 2 only shows two examples of the autotrophic mode. The completed test on the left side of Figure 2 is more elaborate (i.e. especially the part of the process where the Calvin cycle takes place), although there are also some mistakes and elements missing. The completed test on the left side scored nine points and the test on the right side five points.

Data Analyses

First, all variables were normalized on the basis of the mean and standard deviation of the specific learning task. The rationale behind this normalization was that we use a within-students design where the responses to different learning tasks can be considered as responses to different tests (i.e. a multivariate model). Normalization at the level of the learning task allowed us to focus on differences in student behavior and comprehension score instead of differences evoked by the content or design of the diagrams. For

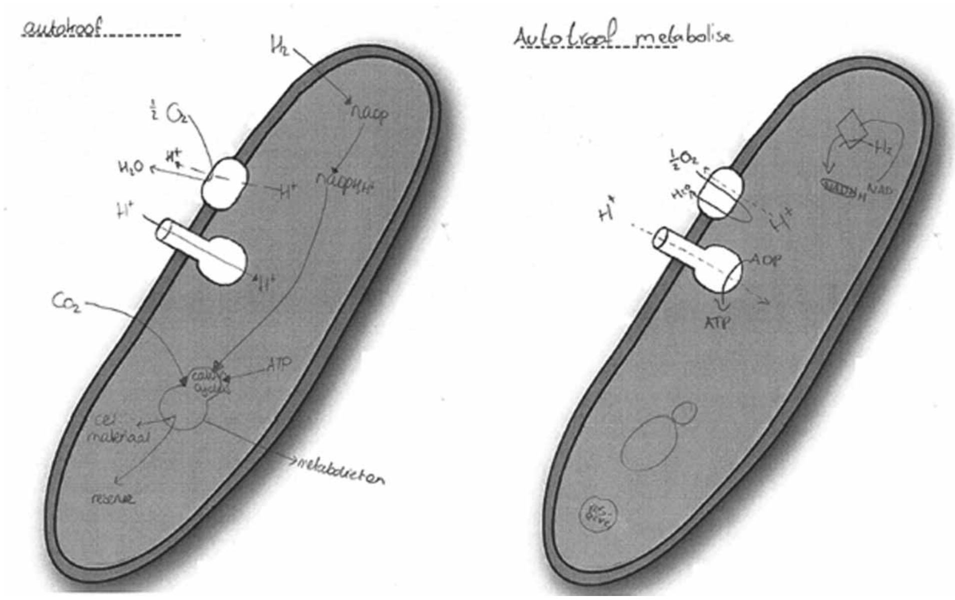

Figure 2. Examples of the completed comprehension test of two students (i.e. only the autotrophic part of the test is shown)

example, a more informative diagram would likely produce more utterances. After normalization, all variables can be interpreted as student's behavior or comprehension score compared to the other students within the particular learning task. The latter allowed us to also analyze between-student and within-student between-diagram differences in behavior and comprehension score across learning tasks.

The first research question was answered by applying the two-level multilevel model presented in Equation 1 (i.e. student level = j and diagram level = i) with students' comprehension score as the response variable (y_{ij}) and learning activity variables as fixed-effect explanatory variables.

$$\begin{aligned} y_{ij} &= \beta_{0ij} + \beta_1 \cdot x_{1ij}, \\ \beta_{0ij} &= \beta_0 + u_{0j} + e_{0ij}. \end{aligned} \quad (1)$$

The random part includes the between-students residuals (u_{0j}) and the within-students between-diagrams residuals (e_{0ij}). The fixed part includes β_0, that is, the grand mean, and β_1, that is, the regression coefficient of an added explanatory variable. Note that β_{0ij} is the intercept-only model if is omitted. For each prediction of the response, we extended the intercept-only model with one explanatory variable ($\beta_1 \cdot x_{1ij}$) at a time. We did not extend the model to contain multiple explanatory variables. This would place too many restrictions on a model because not all explanatory variables could be obtained from the three learning tasks (Tables 1 and 2). We tested whether the intercept-only model was improved by adding a fixed-effect variable by calculating the χ^2 likelihood-ratio (Hox, 2010) with one degree of freedom (i.e. one explanatory variable added). The statistical significance of the fixed effect (β_1) was tested using a two-sided Wald z-test (Hox, 2010). Furthermore, we calculated the amount of variance explained per level, that is, student (σ_u^2) and diagram (σ_e^2), after adding the fixed effect to the intercept-only model (Hox, 2010, p. 71). The amount of variance explained per level might decrease, or even increase (Snijders & Bosker, 1994), depending on the distribution of the explanatory variable within the levels (Hox, 2010). Therefore, we calculated the intraclass correlation (ICC) (Hox, 2010) of each explanatory variable which provides the distribution of the variance on the student level and diagram level. In short, we alternately added a fixed-effect variable to the intercept-only model and then tested the model for significant improvement, the significance of the fixed effect, and the change in explained variance per level.

The second research question was answered by correlating the normalized scores of the learning activities. Only those learning activities that were shown to be related to the comprehension scores were included. The correlation coefficients provided insight into possible dependencies between successful learning activities, indicating whether students use a coherent set of successful learning activities across the three learning tasks.

Results

Learning Activities Related to Comprehension of the Diagram

In Table 3, we present the regression coefficients of the models (see Equation 1) with a single fixed learning activity variable as the explanatory variable and comprehension score as the response variable.

From the variables in the orientation phase, Orientate Legend ($\beta_1 = .42$, $p = .01$) and Orientate Prior ($\beta_1 = .68$, $p = .04$) were significant predictors of comprehension score. Student variance explained by adding Orientate Legend as a fixed effect to the intercept-only model is 17.4%, χ^2 (1, $N = 29$) = 5.53, $p < .05$. Adding Orientate Prior to the intercept-only model explained 6.1% of student-level and 6.9% of diagram-level variance, χ^2 (1, $N = 58$) = 6.44, $p < .05$. The ICC of Orientate Prior was 50.9% on the student ($\rho_{student}$) and 49.1% on the diagram level ($\rho_{diagram}$).

From the variables in the main phase, Meaning Arrow ($\beta_1 = .59$, $p < .001$), Self-Questioning ($\beta_1 = .28$, $p = .02$), Read Title ($\beta_1 = .21$, $p = .05$), and Read Level ($\beta_1 = .30$, $p = .01$) appeared to be significant predictors of comprehension score. Adding Meaning Arrow to the intercept-only model explained 79.6% of student-level and 1.3% of diagram-level variance, χ^2 (1, $N = 58$) = 23.63, $p < .001$. The ICC of Meaning Arrow was 41.1% on the student level and 58.9% on the diagram level. The variable Self-Questioning explained 4.8% of the variance on the student level and 10.49% on the diagram level compared to the intercept-only model, χ^2 (1, N = 58) = 5.13, $p < .05$. The ICC of Self-Questioning was 44.1% on the student level and 55.9% on the diagram level. The intercept-only model was not improved by adding the variable Read Title, χ^2 (1, $N = 58$) = 3.20, $p > .05$. Adding the variable

Table 3. Regression coefficients of single-variable fixed-effects models with comprehension score as dependent variable and ICCs of the explanatory variables

Variable	β_1 (SE)	p	σ^2 explained (%) per level[a]		ICC (%)	
			Student	Diagram	$\rho_{student}$	$\rho_{diagram}$
Orientation phase						
Orientate Title*	.35 (.21)	.11	−0.6[b]	6.1	47.2	52.8
Orientate Level	.20 (.25)	.43	9.3	−4.3	47.8	52.2
Orientate Legend*	**.42 (.17)**	**.01**	17.4		100.0	
Orientate Prior*	**.68 (.32)**	**.04**	6.1	6.9	50.9	49.1
Main phase						
Meaning Arrow***	**.59 (.10)**	**<.001**	79.6	1.3	41.1	58.9
Relate Prior	.21 (.12)	.08	11.9	1.5	23.2	76.8
Alt. Hypotheses	−.05 (.11)	.66	−4.2	2.6	1.7	98.3
Compare	.15 (.12)	.23	4.2	1.5	37.9	62.1
Self-Questioning*	**.28 (.12)**	**.02**	4.8	10.4	44.1	55.9
Meta reread	.02 (.13)	.85	3.0	−1.5	39.9	60.1
Read Title[c]	**.21 (.10)**	**.05**	−22.4	18.4	0.0	100.0
Read Level*	**.30 (.12)**	**.01**	21.8	2.4	37.0	63.0
Use Legend	.25 (.18)	.17	6.2		100.0	
Eye-tracking measures						
Fixation Time Main***	**.51 (.09)**	**<.001**	64.8	6.7	55.5	44.5
Fixation Time Title	.15 (.10)	.14	−4.3	4.4	36.0	64.0
Fixation Time Level	.14 (.10)	.15	9.6	0.0	26.0	74.0
Fixation Time Legend	.13 (.12)	.28	7.2	0.0	2.4	97.6
Transitions Main**	**.29 (.11)**	**.01**	26.7	0.8	54.1	45.9
Transitions Title	.02 (.09)	.82	−0.7	0.2	10.7	89.3
Transitions Level	−.04 (.09)	.65	−4.5	1.7	15.1	84.9
Transitions Legend	.21 (.13)	.10	8.1	3.0	25.0	75.0

Notes: Significant regression coefficients (Wald z-test) are in boldface. β_1 = regression coefficient of the explanatory variable (see Equation 1). ICC = Intraclass correlation of the explanatory variable; an indication of the proportion of variance at the student level and diagram level (Hox, 2010, p. 15).

[a]Variance explained (Hox, 2010, p. 71) after adding a single fixed-effect variable compared to the intercept-only model. Student-level and diagram-level variance of the intercept-only model for comprehension score (i.e. the response variable) per combination of diagrams is: diagrams 1, 2, and 3 ($\rho_{student}$ = 46%; $\rho_{diagram}$ = 54%), diagrams 1 and 2 ($\rho_{student}$ = 52%; $\rho_{diagram}$ = 48%), diagrams 2 and 3 ($\rho_{student}$ = 37%; $\rho_{diagram}$ = 63%).

[b]Note that variance on individual levels can also increase (e.g. Snijders & Bosker, 1994).

[c]Regression coefficient is significant (Wald z-test), but likelihood-ratio test shows that the intercept-only model is not improved by adding this variable. Read Title will not be used in following analysis.

*$p < .05$, χ^2 likelihood-ratio test with df = 1.

**$p < .01$, χ^2 likelihood-ratio test with df = 1.

***$p < .001$, χ^2 likelihood-ratio test with df = 1.

Table 4. Correlation matrix of students' learning activities that are related to the comprehension score

	1	2	3	4	5	6
1. Orientate Legend						
2. Orientate Prior	−.03					
3. Meaning Arrow	.50**	−.04				
4. Self-Questioning	.01	.01	.28*			
5. Read Level	.24	.07	.38**	.17		
6. Fixation Time Main	.36*	.27*	.58***	.48***	.47***	
7. Transitions Main	.28	.43**	.17	.24	.23	.63***

*$p < .05$.

**$p < .01$.

***$p < .001$.

Read Level to the intercept-only model explained 21.8% of the variance on student level and 2.4% on diagram level, χ^2 (1, $N = 58$) = 5.67, $p < .05$. Read Level had an ICC of 37.0% on the student level and 63.0% at the diagram level.

From the eye-tracking measures, the variables Fixation Time Main ($\beta_1 = .51$, $p < .001$) and Transitions Main ($\beta_1 = .29$, $p = .01$) appeared to be significant predictors of comprehension score. Adding Fixation Time Main as a fixed effect to the intercept-only model explained 64.8% of the variance on student level and 6.7% on diagram level, χ^2 (1, $N = 87$) = 23.23, $p < .001$. The ICC of Fixation Time Main was 55.5% at the student level and 44.5% at the diagram level. The variable Transitions Main explained 26.7% of the variance on the student level and 0.8% on the diagram level compared to the intercept-only model, χ^2 (1, $N = 87$) = 6.68, $p < .01$. The ICC of Transitions Main was 54.1% at the student level and 45.9% at the diagram level.

Relationships Between Learning Activities that Significantly Predict Comprehension

Table 4 presents the correlation matrix of learning activities that significantly correlated to comprehension score. Note that all significant correlations were positive. Meaning Arrow was significantly correlated with Orientate Legend ($r = .50$), Self-Questioning ($r = .28$), and Read Level ($r = .38$). Furthermore, Fixation Time Main was significantly correlated with Orientate Legend ($r = .36$), Orientate Prior ($r = .27$), Meaning Arrow ($r = .58$), Self-Questioning ($r = .48$), and Read Level ($r = .47$). Transitions Main was significantly correlated with Orientate Prior ($r = .43$). Finally, Fixation Time Main was correlated to Transitions Main ($r = .63$).

Discussion

Learning Activities Related to Comprehension of Process Diagrams

Orientation phase. We found that the frequency of using the legend and activating prior knowledge in the orientation phase was positively related to students' level of comprehension. The finding that an elaborate orientation phase is related to increased performance is in line with previous research (Pressley & Afflerbach, 1995; Van Gog, Paas, & Merriënboer, 2005).

The variable Orientate Legend, obtained from verbal protocols of learning task 2, explained a medium amount (Cohen, 1988) of student-level variance in comprehension score. It might be plausible to suggest that orientating on the legend at an early stage in the learning process reduces workload in the main phase enabling resources to be used for learning.

Activating prior knowledge in the orientation phase explained a small amount of student-level and diagram-level variance of comprehension score. As mentioned in the theoretical framework, the role of prior knowledge is important for the interpretation of scientific graphical representations (e.g. Cook, 2006). As indicated by the ICC, a fair number of students who activate prior knowledge in the orientation phase do this for both learning tasks.

Main phase. Four predictors were significant for comprehension in the main phase: giving meaning to a process arrow, self-questioning, reading the title, and reading the organizational levels. Reading the title will not be discussed as adding this variable did not improve the intercept-only model (i.e. as indicated by the likelihood-ratio test).

No less than 80% of student-level variance in comprehension score was explained by the number of process arrows a student gave meaning to. Giving meaning to the process arrows seems like a basic activity. When studying process diagrams, arrows are the key signifiers. However, within our group—that is, students with an intermediate level of expertise—it is hard to imagine why some students employ this behavior so minimally. ICCs suggest that the number of process arrows students give meaning to is mostly between-student behavior, that is, within-student between-diagram behavior is consistent across learning tasks.

Self-questioning explained a relatively small amount of student-level and diagram-level variance in comprehension score. The ICCs suggest that a fair amount of variance of self-questioning can be considered as within-student behavior. The significant effect of self-questioning on comprehension score is in line with previous studies (e.g. King, 1989).

Reading the organization levels explained a moderate amount of student-level variance and a small amount of diagram-level variance. Coping with the different levels of organization of biological processes is an important and difficult aspect of learning Biology (Knippels, 2002; Verhoeff, 2003). We suggest that students who actively integrate the hierarchical level of organization in which the process takes place into their visual representation, are likely to understand more of the context, which will, in turn, facilitate understanding. ICCs suggest that reading the levels of organization is mostly within-student between-diagram behavior, that is, student behavior differs across learning tasks. The labels with the level of organization seemed to be equally informative in the diagrams (i.e. unlike the legends in diagrams 2 and 3), suggesting that this is an effect of differences in size, position, or saliency (Cook et al., 2008; Lowe, 1999).

Eye-tracking measures. The eye-tracking measures Fixation Time Main and Transitions Main were significant predictors of comprehension score; Fixation Time Main explained 65% of the between-student variance of comprehension score (cf Mason et al., 2013; Schwonke et al., 2009). These findings support previous findings where fixation time is associated with ongoing cognitive processes (Hannus & Hyönä, 1999; Just & Carpenter, 1976; She & Chen, 2009) and where transitions are associated with integration processes (Mason et al., 2013; Schwonke et al., 2009). Fixation Time Main might negatively influence comprehension of unsuccessful students' because they are satisfied with their learning progress in an early phase as they are not able to detect gaps in their knowledge (Chi, 2000). ICCs of Fixation Time Main and Transitions Main (i.e. measured on all three learning tasks) suggest that a fair amount of variance of both variables can be attributed to between-student differences. The latter suggests that students behave consistently across the learning tasks with regard to ongoing cognitive and integrative processes.

Relationships Between Learning Activities that Significantly Predict Comprehension Score

Relationships between variables from verbal protocols. The significant correlations between, on the one hand, Meaning Arrow and, on the other hand, Orientate Legend, Self-Questioning, Read Level, and Fixation Time Main suggest that giving meaning to process arrows indicates a strategic and in-depth approach for interpreting process diagrams, that is, planned behavior (Pressley & Afflerbach, 1995). The significant relations between Self-Questioning, Meaning Arrow, and comprehension score, may reflect a sequential path of reasoning found throughout the collected verbal protocols. When students gave meaning to one or several process arrows, they often uttered questions that focused on the meaning of these arrows. Attempts to answer these questions might lead to inferences and thereby to a higher comprehension score.

Relationships between variables from verbal protocols and eye-tracking measures. The relationship between fixation time and learning activities supports the idea that increased fixation time indicates the occurrence of in-depth cognitive processing. The high correlation between Fixation Time Main and Transitions Main suggests that students with longer total fixation time in the main area revisited more different parts in the main area.

Limitations

The target group of the present study might be considered a limitation. The learning activities employed by this target group might be specific for students with their level of expertise and experience with studying process diagram. For this, we recommend caution in extending the results to other target groups such as lower grade students and university students. However, the choice for this target group in the present study was deliberate. These students might soon be faced with even more difficult process diagrams in higher education (Dos Santos & Galembeck, 2015). They might face some serious challenges in their study and future careers if their skills for learning from process diagrams are insufficient. Another limitation might be the specific focus on biological process diagrams. Despite this focus, we expect that our results extend to learning from process diagrams in nearby scientific domains (e.g. chemistry, physics) and even to some more distant domains like geography.

Conclusion and Implications for Education

In sum, the present study adds a fine-grained analysis of learning from a specific diagram type, that is, the process diagram, to previous research on learning from graphical representations. We found various learning activities that distinguished more and less successful students while learning from 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 main phase, successful students more often give meaning to process arrows and read the organizational levels. The latter two findings were not found in earlier research. The importance of employing orientating activities is in line with previous research (Pressley, 2000; Pressley & Afflerbach, 1995; Van Gog, Paas, & Merriënboer, 2005). However, the present study adds to existing insights that applying a specific diagram activity, that is, using the legend in the orientation phase, is important as well.

In accordance with previous studies, we also found that successful students were more likely to employ learning activities such as activating prior knowledge (Pressley, 2000; Pressley & Afflerbach, 1995), self-questioning (e.g. Azevedo & Cromley, 2004) and spending more time in the main area of the process diagram (cf Mason et al., 2013; Schwonke et al., 2009; She & Chen, 2009).

We also found that students employed successful learning activities consistently across learning tasks: the learning approaches seemed to be stable. The present study thereby contributes to research that focused on the generalization of (meta)cognitive activities across tasks or domains (e.g. Meijer et al., 2006; Veenman, 2012). Furthermore, we conclude that successful students use a more coherent approach of interrelated learning activities for comprehending process diagrams than unsuccessful students.

The present study provides relevant insights into the topics of a training that specifically focuses on learning from process diagrams. The training could teach students when and how to employ cognitive and metacognitive strategies found to be characteristic for successful students in the present study.

Disclosure statement

No potential conflict of interest was reported by the authors.

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