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Understanding pictorial information in biology: students' cognitive activities and visual reading strategies

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ABSTRACT

In classroom, scientific contents are increasingly communicated through visual forms of representations. Students' learning outcomes rely on their ability to read and understand pictorial information. Understanding pictorial information in biology requires cognitive effort and can be challenging to students. Yet evidence-based knowledge about students' visual reading strategies during the process of understanding pictorial information is pending. Therefore, 42 students at the age of 14–15 were asked to think aloud while trying to understand visual representations of the blood circulatory system and the patellar reflex. A category system was developed differentiating 16 categories of cognitive activities. A Principal Component Analysis revealed two underlying patterns of activities that can be interpreted as visual reading strategies: 1. Inferences predominated by using a problem-solving schema; 2. Inferences predominated by recall of prior content knowledge. Each pattern consists of a specific set of cognitive activities that reflect selection, organisation and integration of pictorial information as well as different levels of expertise. The results give detailed insights into cognitive activities of students who were required to understand the pictorial information of complex organ systems. They provide an evidence-based foundation to derive instructional aids that can promote students pictorial-information-based learning on different levels of expertise.

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Visual reading strategies; cognitive activities; thinking aloud; diagrams; pictorial-information-based learning; biology education

Introduction

Visual representations are essential for scientific communication. The number of line drawings, photographs and diagrams is increasing in scientific journals as well as in learning materials like biology textbooks (Dimopoulos, Koulaidis, & Sklaveniti, 2003; Lee, 2010; Slough, McTigue, Kim, & Jennings, 2010). For many years there has been extensive research regarding the benefits of multi-media-environments, and many studies showed that visual representations can help students to understand scientific texts (Multimedia-principle) (Carney & Levin, 2002; Cook, 2006; Levie & Lentz, 1982; Mayer, 2014). However, in today's learning environments, visual representations are gaining more importance as unique sources of information that are not supplements of the text but must be studied independently (Griffard, 2013; Kragten, Admiraal, & Rijlaarsdam,

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2015). Pictorial information about complex scientific concepts and systems is frequently applied in classroom, as it is supposed to facilitate students' learning. However, it is mostly not considered that understanding pictorial information of complex diagrams requires a lot of self-initiated cognitive effort and prior knowledge (Schnotz, 1997; Schnotz & Kulhavy, 1994). Many studies report that students tend to catch pictorial information only superficially and do not achieve the intended learning outcomes (Cheng & Gilbert, 2014; Cook, Carter, & Wiebe, 2008; Eilam, 2013; Guthrie, Weber, & Kimmerly, 1993). Therefore, actual research is concerned with learners' cognitive activities during the process of understanding visual representations (Griffard, 2013; Kragten et al., 2015; Schnotz et al., 2014). In most cases, the representations used in the studies contain pictorial as well as textual elements. However, given the increasing importance of pictorial information in today's learning environments, more research about specific strategies of pictorial information processing is needed (Schnotz et al., 2014). Knowledge about students' visual reading strategies is important for teaching as it could be applied to develop instructional aids that specifically address learners' needs, in connection with the pictorial information in difficult and complex or sometimes even poorly designed learning materials. Therefore, the analysis of the structure, frequencies and interrelation of students' cognitive activities while they try to understand visual representations of complex organ systems is the subject of this paper.

Theoretical background

Cognitive models of processing pictorial information

Visual representations are two-dimensional pictorial messages that are produced by a graphic designer to communicate information about a certain content. They depict a selection of spatial or functional relationships and structures as models of phenomena by means of representational codes such as topic specific icons, symbols and colour coding (Fenk, 1997; Foley & Buckendahl, 2013; Hegarty, 2011; Weidenmann, 1994a). Empirical studies showed that visual representations can help students to understand scientific concepts faster and longer-lasting compared to the learning with text alone (Carney & Levin, 2002; Levie & Lentz, 1982). Object characteristics such as form, colour and structure as well as spatial and functional relationships can be perceived a lot more efficiently through visual representations than through texts (Schnotz & Kulhavy, 1994; Weidenmann, 1994a). It does not require a lot of cognitive effort to recognise a familiar object in a photograph because the cognitive system uses visual routines such as outline recognition to automatically perceive the depicted content (Schnotz, 1997; Weidenmann, 1994b).

However, visual representations that are used as learning material in biology often differ from simple photographs of familiar objects. They depict complex concepts or systems, such as the patellar reflex or the blood circulatory system (Bredekamp, 2008; Coleman, McTigue, & Smolkin, 2011). In order to represent these concepts visually, the graphic designers make use of very diverse representational codes. The code system that is used in visual forms of representations (depictive/ *pictorial*) is fundamentally different from textual representations (descriptive/ *textual*) (Schnotz, 1997, 2001). Compared to textual codes such as letters and words, representational codes are less conventionalised and 'weak codes' (Weidenmann, 1994b). In other words the meaning of a code can depend on culture, domain and even on a situation (Cheng & Gilbert, 2014; Schnotz & Baadte, 2015). For example, the colours 'blue' and 'red' are representational codes for oxygenated and deoxygenated blood in a diagram of the blood circulatory system, whereas on a water tap blue and red represent cold and warm water. Because of that the comprehension of complex pictorial information requires a deliberate cognitive process of understanding and decoding of codes. Learners have to engage in that process of multileveled cognitive activities (Hochpöchler et al., 2013; Mayer, 2013).

The attentive information processing takes place in the working memory system (Mayer, 2014; Schnotz, 2014). Mayer (1996) describes cognitive activities during pictorial information processing as behaviours and thoughts that a learner engages in during learning and that are intended to influence learner's decoding process and learning outcomes.

Learners have to understand *what* is depicted by representational codes and *why*. Therefore, they have to *select* bits of already perceived information and (re-)*organise* them (Mayer, 2014). This organisation includes relating bits of internal information to a hierarchical system of information. These cognitive activities are based on general cognitive abilities: namely the ability to memorise and apply prior knowledge, for example, about culture-, situation- and subject-specific meaning of the codes (Ainsworth, 2006; Kress & van Leeuwen, 2006; Schnotz, 2014) and the ability to reason coherently (Robinson, 2012; Schraw, McCrudden, & Robinson, 2013). At the end of this process, new information and prior knowledge are *integrated* into an individual system of knowledge, a so-called representation-based mental model (Mayer, 2014; Schnotz, 2014). Therefore, prior knowledge is crucial in determining what impact a visual representation will have on students' cognitive activities (Cook, 2006).

Cognitive activities in connection with pictorial and textual information in biology

Cognitive activities can only be approximated through the observation of statements which students verbalise when they are asked to think aloud during a well-structured learning situation (Ericsson & Simon, 1980, 1998; Kragten et al., 2015). Recent studies describe 'think-aloud activities' while processing biological information of texts and diagrams:

Cheng and Gilbert (2014) reported a case study about students' process of understanding labelled diagrams of the blood circulatory system which students previously encountered in biology class. They interviewed three students and found differences in their proceedings depending on their level of expertise. The lowest achieving student focused on structural details of the diagram and was predominantly 'describing structures'. The students on medium and high levels of expertise furthermore 'described functions' of the different structures and were able to 'infer connections' and describe differences and similarities between representations. Griffard (2013) reported similar findings through analysis of think-aloud protocols of 12 high-school students who were learning with a biological process diagram. Students who successfully interpreted the given representation 'engaged with a clear goal', 'noticed details and graphic cues', 'recalled prior knowledge' and 'identified missing information'.

Kragten and colleagues (2015) analysed retrospective think-aloud protocols of 29 pre-university students who had tried to understand biological process diagrams. According to the results, they were able to differentiate *cognitive-*, *metacognitive-* and *diagram-learning activities* and found that 'giving meaning to a process arrow' was the crucial cognitive activity to explain variance in students' comprehension scores. Furthermore, this activity seemed to be correlated to the activities of 'reading the textual legend' and textual descriptions that were part of the diagram. Although students received primarily pictorial information in this study, they frequently relied on the textual parts of the information in order to construct the meaning. This result underlines the importance of investigating students' activities connected to pictorial information alone. It is questionable to what extent they would cognitively engage in trying to construct the meaning of the representational codes without any textual labelling although this would indicate a form of pictorial key competence, which is essentially required not only in science classroom but in everyday life. The correlations between different variables of cognitive activities that were found in this study indicated that certain activities often appear together and should not be considered isolated in relation to learning outcomes. Rather it is reasonable to further investigate specific sets of activities that sum up to successful visual reading strategies.

In summary: The reviewed studies concerning cognitive activities while reading a text–diagram combination consistently describe the following three activities in connection to the pictorial information: (1) Recall and state prior knowledge (Griffard, 2013; Guthrie et al., 1993; Kragten et al., 2015), (2) Name structures and functions (Cheng & Gilbert, 2014; Griffard, 2013; Guthrie et al., 1993; Kragten et al., 2015) and (3) Inference by connecting single bits of information (Cheng & Gilbert, 2014; Guthrie et al., 1993; Kragten et al., 2015).

However, these results can only be used for very limited predictions as they refer exclusively to reading text–diagram combinations and as they are based on sample sizes in a range from three to 29 students.

Furthermore, most studies we reviewed so far differentiated categories of single cognitive activities and described their interrelationships only rudimentarily. Sometimes single activities were connected to a better learning outcome – for example, 'giving meaning to a process arrow' (Kragten et al., 2015). Actually it is more likely to be assumable that successful understanding of diagrams requires a set or sequence of multiple cognitive activities, a so-called *visual reading strategy*. Research that focuses on the analysis of the interrelationships between students' cognitive activities to clarify the characteristics of visual reading strategies is still rare (Kragten et al., 2015; Lenzner & Schnotz, 2009; Schnotz et al., 2014).

Research questions

Due to the increasing importance of pictorial information in today's learning environments, evidence-based knowledge about the specific characteristics of different visual reading strategies is a necessity for professional teaching with visual representations (Cheng & Gilbert, 2014). Based on a deeper understanding of students' visual reading strategies while trying to understand pictorial information, teachers could evaluate learning processes, prompt effective learning behaviour or construct individualised learning material even more efficiently.

Therefore, our study addressed the following research questions (RQ):

- RQ 1: Which categories of students' cognitive activities can be differentiated when they try to understand pictorial information about blood circulation or about patellar reflex?

- RQ 2: To what extent can patterns of interrelated cognitive activities be derived and interpreted as visual reading strategies?

Design and methods

Procedure

Students were familiarised with the goal of the study and the method of thinking aloud. They initially were motivated to state anything they think in their own words and instructed how to think aloud while answering three questions not related to a biological content.

After the initial training phase, each participant was provided with one diagram at a time per content. One content was blood circulatory system and the other was patellar reflex. Participants were instructed to explain in any amount of detail how they understood it and how they proceeded while trying to understand the diagram. Maximum time per diagram was limited to fifteen minutes, which was largely enough for all participants. All participants were recorded individually in order to document each verbal statement. The data collection took place in students' science classrooms during a 90-minute lesson. A maximum of eight students were tested simultaneously. The recordings of students' statements were transcribed into protocols of thinking aloud. These were categorised and analysed using a mixed-method approach.

Participants

Forty-two students from three different schools and six different classes volunteered to participate in the study. All students were aged between 14 and 15 years and attended the higher track of the German secondary school system (Gymnasia). Of the total participants, 52% were females.

Diagrams

Each student had to think in connection with two diagrams. One diagram depicted the blood circulatory system and the other one depicted the patellar reflex. To refer to everyday science classroom, the design of the diagrams was closely related to the way the blood circulatory system and the patellar reflex are usually presented to students in biology textbooks (see Coleman et al., 2011). The diagram of the circulatory system depicted human blood in different colours for oxygenated and deoxygenated blood and its circulation through lungs, heart and body (Figure 1). The diagram of patellar reflex depicted signal trigger, activation of afferent neurons, signal processing, efferent motoric neurons and the reaction of involved muscles (Figure 4, p. 19). Both contents are connected to the following national standard for biology education in German curriculum: 'Students describe and explain the structure and function of organs and organ systems […]' (KMK, 2005, p. 13). According to the German curriculum, the blood circulatory system is an obligatory

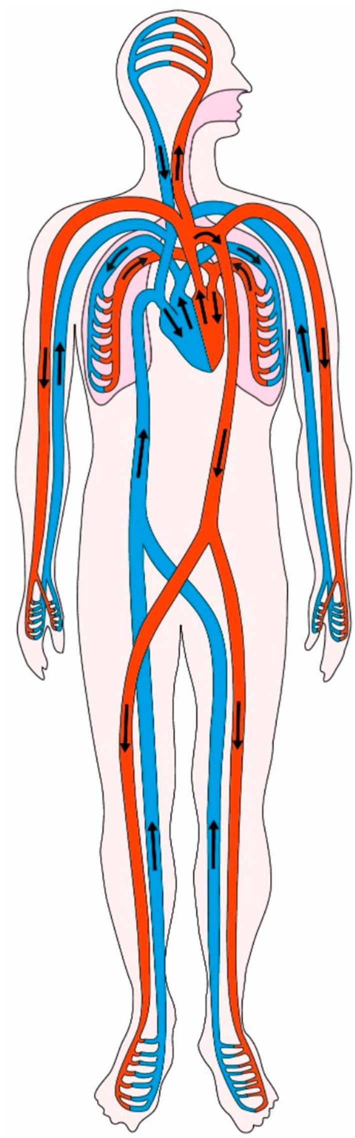

Figure 1. Diagram of the blood circulatory system designed by the authors.

topic for younger students at the age of ten to twelve, whereas the patellar reflex is an optional topic for older students at the age of 14–15. Therefore, it was assumable that participants' prior content knowledge about the blood circulatory system would be more elaborated than their knowledge about patellar reflex.

Deriving a category system of cognitive activities in connection with pictorial information

In order to be able to analyse cognitive activities, the recorded think-aloud sessions were transcribed and individual protocols for each student and each diagram were generated on statement level ($N = 84$ protocols). In other words, students' flow of speech was cut into single analytic propositions, which were defined as unit of analysis. Overall $N = 4351$ single statements regarding the diagrams were observed. The average amount of statements per student and diagram was $M = 52.15$ (SD = 26.92) within a range from at least 11–146 statements. Defining units of analysis, like it was done here, is not only a very extensive work to do, it is essential for being able to count and compare frequencies or do further statistical analysis based on the verbal data. After data preparation a category system of cognitive activities during the process of understanding pictorial information was derived from the theories of information processing (Mayer, 2014; Schnotz, 2014) and from evidence on activities during text-diagram integration (Cheng, Maurice M. W. & Gilbert, 2014; Griffard, 2013; Kragten et al., 2015) through Iterative Content Analysis (Mayring, 2010). At least one category was applied to each single statement. For reliability and validity insurance two independent raters applied the final category system to 30% of the students' statements (Mayring, 2010). Interrater reliabilities for each category of cognitive activity frequencies were measured using Intraclasscorrelation (ICC_{unjust}). Coefficients bigger than .7 can be held as satisfactory (Wirtz, 2002).

Modelling visual reading strategies as patterns of cognitive activities

Visual reading strategies can be observed as specific patterns of cognitive activities which students verbalise when they are asked to think aloud dealing with pictorial information. They consist of a set of different cognitive activities and potentially promote the learning effect. To derive visual reading strategies, a Principal Component Analysis (PCA) with orthogonal rotation (VARIMAX) was conducted. The intension was to clarify the directions, strengths and structure of the interrelationships between categories of single cognitive activities (Bos & Tarnai, 1989; Lind & Sandmann, 2003). PCA clusters single cognitive activities to a set of multiple cognitive activities, so-called underlying factors. Due to the orthogonal rotation, cognitive activities that load on one factor are highly correlated, whereas cognitive activities on different factors appear independently from each other during the process of understanding pictorial information. Factors that resemble a consistent content pattern of cognitive activities are permitted to be interpreted. That means conducting a PCA that leads to interpretable underlying factors can also be held as an indicator for the validity of the category system of cognitive activities. It suggests that the assignment of the verbal statements to the categories of cognitive activities has been reliable and that the raters have consistently interpreted the meaning of the categories.

After conducting the PCA and interpreting its quantitative results, we looked back into the original data of verbal statements to reassure the extent, the relatedness and representativeness of our quantitative results to the original qualities of the think-aloud statements of our participants.

Furthermore, factor scores were obtained by regression method ($-1.5 <$ maximum range < 4.4; $M = .00$, SD = 1.00) to analyse the relation between the two different contents and the quality of participants' patterns of cognitive activities. A high factor score on a certain factor indicates that participant's cognitive activities during the representation-based learning situation were highly consistent with the extracted pattern of the factor, whereas a low score indicates that the participant showed that pattern of cognitive activities less consequently during the learning situation. Spearman's correlation (r_s) was applied to analyse the relationship between content and patterns of cognitive activities.

Results

Quality and frequencies of students' cognitive activities

16 categories of different cognitive activities were differentiated during students' process of understanding the pictorial information of the blood circulatory system and the patellar reflex. These cognitive activities were sorted into a hierarchical system of categories with three levels. On the first level, 79% of all statements resembled '1. Activities in response to the depicted content' (Figure 2). 12% of the statements included '2. Activities in response to the design of the diagram'. Statements that belonged to that category basically dealt with valuing the design of the diagram and improvement suggestions. 9% of the statements could be categorised as '3. Activities in response to one's individual state'. Statements on general mis-, understanding and on the self-concept in biology typically represent that category of activities.

It was possible to subdivide '1. Activities in response to the depicted content' further into the following subcategories of cognitive activities: '1.1 recalling of relevant prior content knowledge', '1.2 naming of depicted codes and structures' and '1.3 constructing the meaning of a code/ structure'. Sixty-four per cent of all of these statements indicated selection processes and identification activities (Figure 3; 1.2). Thirty-two per cent of the statements resembled the construction of meaning (1.3) and 4% of the statements included prior content knowledge facts (1.1).

On the third level of the category system, there were two different qualities of the way students *named depicted codes and structures* and at least eight differentiable steps of the *meaning-making process* to be observed. Table 1 shows the final category system that describes students' activities during the process of understanding pictorial information, absolute and relative activity frequencies over all statements as well as typical examples of students' statements. Interrater reliability was sufficient for the categories (ICC_{Mdn} = .703).

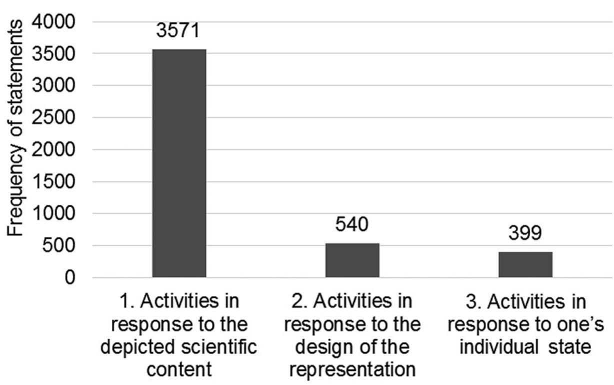

Figure 2. General categories of cognitive activities during the process of understanding pictorial information of the circulatory system and the patellar reflex.

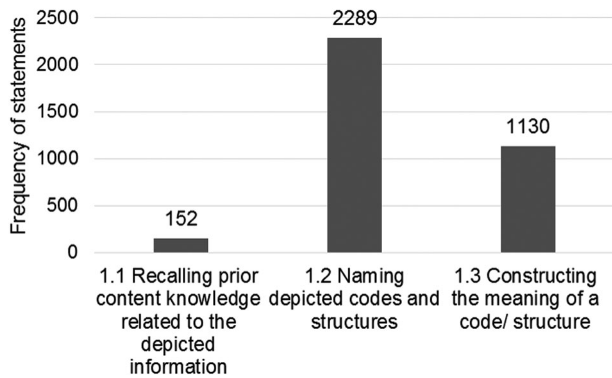

Figure 3. Subcategories of activities in response to the depicted content during the process of understanding pictorial information of the circulatory system and the patellar reflex.

Model of visual reading strategies

By means of deriving underlying factors of the cognitive activities that potentially indicate meaningful patterns of learning behaviour a PCA was conducted on the 16 categories of the system with orthogonal rotation (VARIMAX). The Kaiser–Meyer–Olkin measure verified the sampling adequacy for the analysis, KMO = .717, and KMO values for individual categories lay in a range from .504 to .785 (Mdn = .686). Bartlett's test of sphericity χ^2 (120) = 427.85, $p < .001$ indicated that correlations between categories were sufficiently large for PCA. An initial analysis was run to obtain Eigenvalues for each factor in the data. Five components had Eigenvalues over Kaiser's criterion of 1 and in combination explained 65.12% of the variance. Table 2 shows the factor loadings after rotation. Factor loadings above .5 are highlighted.

Based on the results of the factorial model, the categories, which cluster on the same factors, suggest that:

- Factor 1 represents a cognitive pattern named
  'inferences predominated by using a problem-solving schema',
- Factor 2 represents a cognitive pattern named
  'inferences predominated by the recall of prior content knowledge',
- Factor 3 represents a cognitive pattern named
  'criticism' and
- Factor 4 represents a cognitive pattern named
  'general metacognitive activities.

Cognitive activity patterns of factors 1 and 2 have in common that participants state what is depicted and that they reason about the meaning of the depicted codes. Therefore both patterns can be held as visual reading strategies. According to the distribution of the categories between the two factors, these strategies differentiate in amount and quality of prior content knowledge available in the learning situation.

These findings were supported by the results of the correlation analysis between the two different contents and the factor scores of the extracted visual reading strategies. Spearman's correlation shows significant relationships between the content of the diagram

Table 1. Category system of students' cognitive activities, absolute and relative values of coding and examples of students' statements.

Categories		Examples statements	Σ	%	ICC
1.	Activities in response to the depicted scientific content		3571	79.3	
1.1	Recalling prior content knowledge related to the depicted information	'I know that experiment, my doctor has done it and my leg flipped forward quickly without my support!'	152	3.4	.799
1.2	Naming depicted codes and structures		2289	50.8	
1.2.1	using everyday language	'There are blue and red lines … '	838	18.6	.851
1.2.2	using technical terminology	'In the diagram I can see blood vessels … '	1451	32.2	.752
1.3	Constructing the meaning of a code/ structure		1130	25.1	
1.3.1	Naming codes whose meaning cannot be constructed using everyday language	'I don't know, what the blue arrow means', 'Why is this here lighter and that here above darker?'	297	6.6	.833
1.3.2	Naming codes whose meaning cannot be constructed using technical terminology	'I can't say, why this muscle here is highlighted in every diagram … '	40	0.9	.714
1.3.3	Deriving an assumption about the meaning	'It must be true that there somehow an information is processed'	389	8.6	.859
1.3.4	Rejecting a just constructed meaning	'No that [the meaning] was wrong.'	84	1.9	.576
1.3.5	Constructing an alternative meaning	'[It is not the liver], it is the lung … '	53	1.2	.675
1.3.6	Cross-referencing a constructed meaning to specific information	'Then the muscle contracts, because here it seems shorter and the colour changes from light to dark red.'	111	2.5	.537
1.3.7	Cross-referencing a constructed meaning to prior knowledge	'It is the lung, we learned that blood always has to go through the lung first … '	46	1.0	.701
1.3.8	Reasoning based on constructed meanings	'Probably that muscle has to be relaxed in order to lift the leg … '	110	2.4	.698
2.	Activities in response to the design of the diagram		540	11.9	
2.1	Valuating the diagram	'The diagram is designed really badly.'	389	8.6	.632
2.2	Stating improvement suggestions regarding the diagram	'It would be much easier, if the caption would state more information.'	151	3.3	.903
3.	Activities in response to one's individual state		399	8.8	
3.1	Describing the custom proceeding	'Now I am going to look at the first diagram.'	96	2.1	.705
3.2	Expressing general mis-, understanding	'Ah! I think I got it!'	94	2.1	.501
3.3	Expressing statements on self-concept	'I am not really good in Biology.'	209	4.6	.678
Σ			4510[a]	100	

[a]Overall $N = 4351$ statements were coded. 4196 statements were coded with one single category, 151 statements were coded with two and 4 statements were coded with 3 categories. The indicated relative values refer to the amount of category codes in relation to all assigned codes.

Table 2. Matrix of factor analysis (factor loadings >.5 are highlighted).

Categories		factors				
		1	2	3	4	5
1.	**Activities in response to the depicted scientific content**					
1.1	Recalling and stating prior content knowledge related to the depicted information	.073	**.688**	−.210	.008	.175
1.2	Naming depicted codes and structures					
	using everyday language	**.756**	.174	.053	.065	−.109
	using technical terminology	.126	**.850**	.031	−.020	−.115
1.3	Constructing the meaning of a code/ structure					
	Naming codes whose meaning cannot be constructed using everyday language	**.793**	−.171	.137	.093	.039
	Naming codes whose meaning cannot be constructed using technical terminology	.310	**.557**	.266	−.012	−.458
	Deriving an assumption about the meaning	**.841**	.104	−.158	−.042	.054
	Rejecting a just constructed meaning	**.681**	.303	−.037	−.062	.373
	Constructing an alternative meaning	**.708**	.031	.186	.064	.239
	Cross-referencing a constructed meaning to specific information	**.483**	**.413**	.240	−.248	.247
	Cross-referencing a constructed meaning to prior knowledge	.329	.112	.090	.119	**.788**
	Reasoning based on constructed meanings	−.141	**.608**	−.025	.308	.138
2.	**Activities in response to the design of the diagram**					
2.1	Valuating the diagram	.057	.061	**.863**	.155	−.115
2.2	Stating improvement suggestions regarding the diagram	.060	−.091	**.810**	−.031	.144
3.	**Activities in response to one's individual state**					
3.1	Describing the custom proceeding	−.036	.099	−.060	**.687**	−.055
3.2	Expressing general mis-, understanding	**.515**	−.159	.081	**.522**	.033
3.3	Expressing statements on self-concept	.102	.096	.354	**.678**	.285

and the visual reading strategies of factor 1 and 2. In comparison, the patterns of cognitive activities behind factor 3 and 4 were not significantly related to one of both contents. These patterns occurred independently from the content of the diagram (Table 3).

The inverse directions of the correlation coefficients in Table 3 indicatethat, in the presence of the diagram of the blood circulatory system, participants were more likely to show cognitive activities that were consistent with the visual reading strategy of factor 2. Visual reading strategy of factor 1 was more likely to be expressed in the presence of the diagram of the patellar reflex.

Descriptive analysis reveals that there were 14 participants ($P = 33\%$), that always scored high either on the visual reading strategy of factor 1 or on the strategy of factor 2. Eight participants ($P = 19\%$) did not gain high scores neither on visual reading strategy of factor 1 nor on the strategy of factor 2. There were 20 participants ($P = 48\%$) to be observed, that gained a high score on the visual reading strategy of factor 2 in the presence of the diagram of blood circulatory system and at the same time a very high score on the visual reading strategy of factor 1 in connection with the diagram of patellar reflex.

Table 3. Spearman's correlation between the contents of the diagrams and participants' factor scores of the extracted patterns of cognitive activities.

	Content[a]		
	r_s	$p_{(one\text{-}tailed)}$	*N*
Factor 1: 'Inferences predominated by using a problem-solving schema'	−.405	<.001	84
Factor 2: 'Inferences predominated by the recall of prior content knowledge'	.366	<.001	84
Factor 3: 'Criticism'	.051	.322	84
Factor 4: 'General metacognitive activities'	.019	.433	84

[a]1: blood circulatory system; 0: patellar reflex.

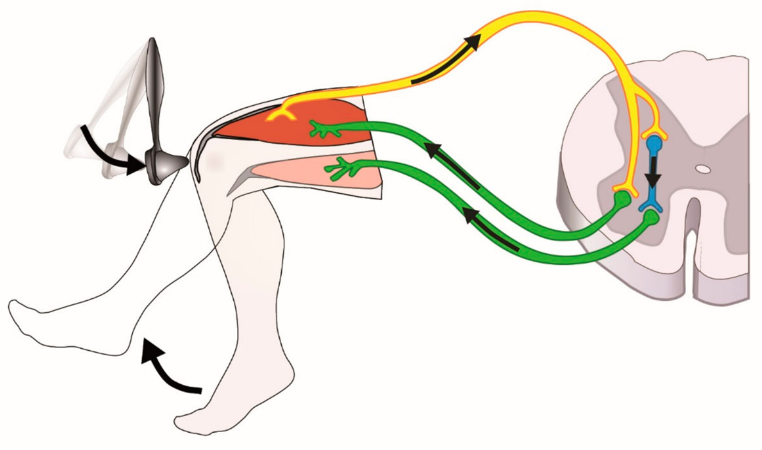

Figure 4. Diagram of the patellar reflex designed by the authors.

Exemplification of the visual reading strategies

To clarify the extent of relatedness between the results of the factorial analysis and the quality of the original verbal data, we reconsidered the think-aloud protocols of our participants, trying to identify participants that showed at least one of the two extracted visual reading strategies in a stereotypic manner.

Participants who gained a high factor score on the visual reading strategy named 'inferences predominated by using a problem-solving schema' were more likely to act like *Tom* who participated in the study and processed the information of the diagram of the patellar reflex (Figure 4) and whose extract of verbal data is stated below.

> In this leg here, I really do not understand why this shaft here is represented so much brighter than that one above [He is pointing at the Quadriceps]. It must have a meaning. Mmmh, no idea! I think, definitely there is some stimulus that is somehow processed by that way. Okay that muscle here is darker, and … . I just got the idea! Maybe it means, that it contracts and the other stretches. But honestly, no idea if this is true, and mmh … I don't know, here this strange yellow line and there it is two-tiered and these odd green ones. Well, this yellow is somehow first one and then becomes two. Why are there suddenly two? Oh, I see, there is somehow a stimulus and the stimulus is then transmitted by the nerve cord, tendon or somewhat, how shall I know, and then … . But wait, this strange grey butterfly, isn't it the brain or somewhat? No, I was wrong! This yellow is not the tendon, it is the nerve cord. (Translated from German)

Therefore, *Tom's* original verbal data suggest that he selects representational codes with and without the usage of technical terminologies whose meaning is unclear to him. He states an assumption while reflecting on his understanding. He finally tries to justify his assumption by integrating it into the global information of the process diagram. He is focused on the information that is depicted through the representational codes and tries to construct logical meaning.

The extract of *Tom's* verbal data exemplifies a cognitive activity pattern that is quantitatively dominated by the recall of bits of external information and a recall of common knowledge and its integration by using a problem-solving schema.

Participants who gained a high factor score on the visual reading strategy named 'inferences predominated by the recall of prior content knowledge' were more likely to act as *Charlotte* who studied the diagram of the patellar reflex as well and proceeded as following while trying to understand the meaning of the representational code which represents the spinal cord:

> I have no idea to what body part that thing belongs [she points at the spinal cord] So maybe the grey thing is a part of the brain … Ehhm … through that part of the knee, where you place the hammer stroke, the signal is forwarded through the body by different nerves into the brain. The signal is converted in the brain and the brain sends feedback because signals are always processed in the brain and through that little experiment you can test the function of the brain. (Translated from German)

The student starts with the selection of a structure to which she fails to construct meaning and states an assumption which is comparable to *Tom's* proceeding. But thereafter *Charlotte* immediately starts to describe the depicted process in detail by using biological terms for different structures and functions. In the end she states prior knowledge and conclusions based on this construction of meaning. Her cognitive activities are dominated by recalls of prior content knowledge and immediate integration of external information.

Charlotte's verbal data suggest that she constructs meaning and tries to infer from the depicted information by taping prior knowledge. She does not describe the information on the level of representational codes, but relates structures to biological terms right away, even though she uses wrong terms.

Both students are studying the same diagram, but proceed in different ways. *Tom* relates more to the representational codes, whereas *Charlotte* tries to construct meaning mainly by referring allegedly to appropriate prior knowledge.

Discussion

Students' cognitive activities when processing pictorial information

In this study, 42 students at the age of 14 were asked to think aloud, while they were trying to understand diagrams of the blood circulatory system and the patellar reflex, in order to get detailed insights into their cognitive activities in connection with pictorial information (*RQ 1*). The analysis of the think-aloud protocols reveal that students' cognitive activities concerning the pictorial information *responded by far the most to the depicted scientific content*. In this study, 79% of all statements resembled cognitive activities that were related to the process of understanding pictorial information. Therefore, the instruction to explain by any amount of detail how students understood the depicted information was very appropriate and sufficient for 14-year-old learners. Additionally, information about complex biological systems solely represented through pictorial elements in this study induced learning activities very sufficiently. Against the background of former findings out of the field of learning with combinations of texts and pictures (Kragten et al., 2015), it initially had been fundamentally questionable to what extent students would concentrate on this kind of learning material that was exclusively image-based. Especially in the context of communicating scientific concepts, pictorial information is mostly regarded as supplement to textual information.

Besides the cognitive responses to the depicted content, the participants *responded to their individual state* and *to the design of the diagram*. The latter can be interpreted as an artefact of this study as most of the statements of this category were concerned with the criticism that the representation had not been labelled. Obviously, students are not familiar dealing with pictorial information without any textual labels, which does not mean this could not be an effective learning situation.

Analysing the 'cognitive activities in response to the depicted scientific content', we found that students' activities were predominated by *identification* and *meaning-making* processes when they responded to scientific content. These findings are in accordance with the theory of information processing (Mayer, 2013). Identification processes were more frequent than organisation or integration processes. This could be due to the fact that identification processes are a perquisite for further or deeper processing and that they are connected to lower cognitive effort (see Sweller, Ayres, & Kalyuga, 2011). These findings are also in line with previous studies, where students concentrated on *identification* and rarely engaged in the *meaning-making* processes that could promote deeper understanding of the depicted concepts (Cheng & Gilbert, 2014; Griffard, 2013). But does that mean that the students tended to perceive the diagrams only superficially? In this study, 32% of the statements resembled the construction of meaning and some students naturally engaged in diverse, multi-levelled cognitive processes such as asking questions, deriving assumptions, constructing and validating meanings. All these activities are held to be connected to a deeper understanding of codes and structures in visual representations (Mayer, 2013). In this study, students asked questions regarding the diagram; they noticed inconsistencies of their assumptions about the meaning of codes and structures. In comparison, higher order activities such as valuating, proving, rejecting and reconstructing meanings were less frequently observed. In contrast, previous studies that dealt with pictorial information supplemented through textual elements showed that students did even rarely reach the level of asking questions (Kragten et al., 2015). The different findings indicate the question, to what extent the type and amount of textual supplements, such as labels, influence the cognitive depth of processing pictorial information?

At least, the number and qualities of corresponding subcategories in connection with *identification* or *meaning-making processes* in this study might indicate the degree of cognitive effort or even the cognitive load students invested on task-related learning activities (Kalyuga, 2011). The category system describes *identification* processes by only two subcategories, whereas sub-steps of *meaning-making* are represented by eight different subcategories.

Visual reading strategies

Concentrating on the extraction of 'visual reading strategies' as a set or a repertoire of multiple cognitive activities that are shown by the individual learner while trying to understand pictorial information a Principle Component Analysis was conducted (*RQ 2*). According to this analysis, there were four interpretable patterns of cognitive activities that could empirically be differentiated: (1) *Inferences predominated by using a problem-solving schema,* (2) *Inferences predominated by the recall of prior content knowledge*, (3) *Criticism* and (4) *General metacognitive activities*. Pattern 1 and 2 both include cognitive processes of identification, organisation and integration of the depicted scientific content and therefore can be interpreted as visual reading strategies (Chi & Wylie, 2014; Mayer, 2013). However, as anticipated (Cook et al., 2008), they differ regarding the degree or prior content knowledge which is applied, and additionally they differ concerning the structure of the solution process. Visual reading strategy 1 goes along with typical steps of a general problem-solving procedure (Fischer, Greiff, & Funke, 2011; Funke, 2003) such as stating assumptions and questions, proving assumptions by co-referencing, revising assumptions and constructing alternative assumptions. Students, who predominantly show this strategy during the learning situation, focus on naming the codes that constitute the encountered diagram and they try to extract and infer as much new information from the diagram itself as possible. These students use subject-specific and particularly common knowledge about meanings of codes to reconstruct the depicted information.

Visual reading strategy 2 is predominated by the recall of prior content knowledge and immediate integration (Ayres & Sweller, 2014). So, this visual reading strategy is dominated by naming structures and immediately linking the perceived information to prior content knowledge.

The correlations between the contents of the diagrams and the factor scores of the visual reading strategies support the assumption about the impact of prior content knowledge on the quality of visual reading strategies expressed in the learning situation. Students tended to show visual reading strategy 1 more often in connection with the diagram of patellar reflex. Strategy number two was more likely to be expressed in the presence of the diagram of the blood circulatory system. According to the German curriculum, the blood circulatory system is an obligatory topic for younger students at the age of 10–12 whereas the patellar reflex is an optional topic for older students at the age of 14–15. Reconsidering participants' age, it is assumable that prior content knowledge about the blood circulatory system was more elaborated than the knowledge about patellar reflex. Furthermore, the analysis indicated that some students automatically changed the visual reading strategy dependant on the content of the diagram. That indicates adaptive learning behaviour or so-called strategy shifts (Schnotz et al., 2014) during pictorial processing. Therefore, both types of visual reading strategies indicate visual literacy. Our analysis showed that different students use at least two different reading strategies that consist of specific patterns of cognitive activities, during their process of understanding pictorial information. It depends on prior content knowledge to what extent a student primarily focusses on one or the other visual reading strategy. There were also students that were not able to perform one or the other strategy sufficiently, which indicates that these students still lack of visual literacy in need further support.

Previous studies described cognitive activities of students during text-picture-processing (Griffard, 2013; Kragten et al., 2015; Schnotz et al., 2014). Reconsidering the importance of visual forms of representations for science teaching and learning (Mayer, 2013; Roth & Pozzer-Ardenghi, 2013; Slough et al., 2010) and especially the fact that in science complex and diverse visual representations represent unique information increasingly, it was striking that an investigation of students' cognitive activities in connection with pictorial information was still pending. Our study offers differentiated insights in students' cognitive activities and reading strategies while they try to understand pictorial information depicted in diagrams of complex organ systems.

Limitations

Certainly all the results must be treated carefully because they are grounded on a relatively small sample size of 42 students, even if comparable thinking aloud studies usually deal with smaller sample sizes (Cheng & Gilbert, 2014; Griffard, 2013; Kragten et al., 2015). The diagrams we used did not include any textual information or labelling, which is quite unusual to the educational field. Based on cognitive theory, pictorial information is processed slightly different to textual messages or multiple external representations (Mayer, 2014; Paivio, 1986; Schnotz, 2014). In this study the focus lay on pictorial information processing, and therefore text or labels were deliberately omitted. Here, textual labelling would have influenced the content quality of students' statements, especially the usage of technical terminology. With labelled diagrams, cognitive activities such as the self-initiated recall or integration of prior content knowledge could not have been differentiated from just reading out loud the externally represented labels. However, given the increasing diversity of our societies, the form of representations we used in the study can also be valuated as advanced for science teaching environments, since pictorial information in contrast to textual information can be understood independently from mother tongue (Kress & van Leeuwen, 2006).

Additionally, a crucial aspect here is that the results are not related to measures of the learning outcomes or to measures of the levels of prior content knowledge. Furthermore, students' statements during the think-aloud session while trying to process the pictorial information can only be understood as approximation of underlying cognitive activities.

Conclusions

Being literate in science and engineering requires the ability to read and understand their literatures (Norris & Phillips, 2003). In today's world understanding visual forms of representation is increasingly important. Learning materials, paper based and virtual media, heavily rely on these forms of representation (Treagust & Tsui, 2013). In order to be able to support students' understanding of visual representations through effective learning materials, more research about specific strategies of pictorial processing is needed (Schnotz et al., 2014). This study contributes qualitative insights in students' cognitive activities while understanding diagrams of organ systems in biology.

According to our results, we can state that even 15-year-old students sufficiently engage in *identification* and *meaning-making* processes in connection with complex diagrams of the blood circulatory system and the patellar reflex. These activities are obligatory in order to understand visual representations in biology and students should be given enough time in classroom to do so.

According to theory (Anderson, 1981; Ericsson & Smith, 1991; Friege & Lind, 2006), it is assumable that both visual reading strategies 1 and 2 indicate expertise in pictorial information processing of biological contents. Students that show visual reading strategy 1 can be held as experts in a closely related content field with a slight lack of prior knowledge about the depicted content. To support this assumption, both kinds of visual reading strategies should be correlated with high learning outcomes and both groups of learners should have gained satisfactory biology grades. Another supporting evidence would be that both groups of learners significantly differ in the level of corresponding prior content knowledge as well as in the level of self-reported cognitive load. Deriving that kind of evidence is going to be part of our upcoming work as well as the question about strategy shifts of learners as an adaption to changing learning conditions (Schnotz et al., 2014). In accordance to our results, it is likely that students could be able to change their visual reading strategies in dependence of their individual degree of prior knowledge on the depicted content, but would they also change their visual reading strategy in dependence of certain design features of the diagrams? Are there external factors that can easily be manipulated by the teacher that correlate with a certain, intended learning behaviour? We try to address these questions soon.

Implications for teaching and learning

So far, the results of this study consistently indicate that learning materials representing complex organ systems solely through pictorial elements activate students' learning very sufficiently. *Pictorial-information-based learning* even lead to higher order cognitive processes, which might induce a deeper understanding. Therefore, *pictorial-information-based learning* might be attractive when introducing new scientific concepts right at the beginning of a learning sequence. According to the results, visual literate learners will then engage in inferences using problem-solving schemas to evolve their individual understanding.

The findings also indicated that 19% of the participants at the age of 15 was not able to perform one or the other visual reading strategy satisfactory. Those students still need to learn how to read pictorial information. The detailed descriptions of cognitive activities in connection with *pictorial-information-based learning* of this study can be used to develop example-based trainings or learning tasks to promote visual reading strategy learning.

Furthermore, the category system can be used to develop diagnostic tools that assess students' expertise in using visual reading strategies. These could be small steps to help students to understand the information in visual representations in class but teaching and learning science is far more than reading information. Usually reading information in science class is connected to even more complex learning situations, for example during experimentation. Our future work will therefore address the effects of pictorial-information-based learning in even more complex scientific learning environments.

Disclosure statement

No potential conflict of interest was reported by the authors.

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