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Common Mistakes in the Construction of Diagrams in Biological Contexts

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Introduction

Relevance of Diagrams

Understanding diagrams plays an important role in everyday life, for example, if we want to understand the results of an election or properly interpret the graphic representation of news from the stock exchange. Electronic media in particular (AV media and computer-supported systems such as televisions, smartphones and tablet PCs) are increasingly using more graphic representations and visual symbol systems to simplify user guidance and present complex information in their online and offline ranges. One presumed advantage of these visual schematic illustrations is that links and relationships among data can be perceived more rapidly and vividly than if they were sequentially described in literary language (Kuckartz et al. 2010). This is one reason why graphics and other visualisations are often used in science in particular (Roth et al. 1999). In addition, it has been shown that the independent and active construction of diagrams by learners creates an environment that promotes learning (Cox 1999; Stern et al. 2003).

In order to prepare students for a future that will necessitate skills for using graphic representations, the German ministries of education have adjusted their requirements for students. Accordingly, in the German curricula and (national) educational standards, mathematics is no longer the only subject in which students are taught how to interact with diagrams (KMK 2005)—they play a growing role in science. In subjects such as physics, chemistry and biology, the ability to independently construct and evaluate graphic representations of data is defined as an educational objective (Lachmayer 2008). In some German curricula, this ability

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is even included in the methodology skills to be taught to students and is a goal of general education (Lachmayer 2008). In summary, the use of graphs and other visualisations occupies a central position both in daily life and in science and schools.

Difficulties in Interacting with Diagrams

Although our educational system views the development of skills for the competent use of diagrams as desirable and many efforts are being made to promote these skills, students still have trouble correctly interpreting or independently constructing diagrams. Studies with scientists have shown that graph-related activities are experience-based, domain-specific and characterised by interpretive resources and practices (Bowen et al. 1999). Since diagrams are not a representational form that can be intuitively understood (Dreyfus and Eisenberg 1990), they are often not properly understood or used effectively even by college graduates with Bachelor and Master of Science degrees (Felbrich 2005; Roth et al. 1998). Kozma (2003) compared chemistry students as novices and chemists as experts in laboratories while interpreting, constructing and integrating multiple external representations, e.g. text and graph. Experts were significantly better than novices at transforming a given representation into a chemically meaningful representation in another form.

Problems in understanding diagrams are often most apparent with tasks that require thematic knowledge to be applied in interpreting a diagram (McDermott et al. 1987). It follows that mathematical knowledge cannot simply be transferred to a science context (Felbrich 2005). This might be explained by the different abstraction levels of mathematical and scientific diagrams. Mathematics commonly uses abstract diagrams that describe the relation between two sets of numbers. In science, in contrast, diagrams generally describe concrete variables that represent data from real contexts (Lachmayer 2008). Therefore, not only math but also science teachers should be trained to consider the audience and context when structuring lessons to give students practice with using diagrams. From a didactic perspective, it is very important that teachers have knowledge about common mistakes and misconceptions so they can choose an appropriate teaching method to help students acquire a proper understanding of diagrams. More research is needed in this area to enable us to systematically describe such common mistakes in the use and construction of diagrams in science.

This study will therefore summarise and systematically describe common mistakes made by students entering university when they construct diagrams in a biological context. An empirically validated structural model of diagram competence is used as an instrument for diagnosing their ability to construct diagrams (Lachmayer et al. 2007). Most studies in this area have focussed on the abilities of primary or secondary students; in contrast, this study analyses the abilities of tertiary students to construct diagrams, so we can identify which previously recognised problems related to diagram construction persist into the tertiary years among students who self-select as science students. With this knowledge about students entering university, we are able to draw conclusions from the knowledge students have at the end of secondary school. Therefore, the results have relevance for both of the following: the didactics of secondary schools because they (probably) failed to sufficiently develop students' abilities to construct diagrams and the didactics of tertiary institutions, which have to consider students' abilities and give them a proper training. Otherwise, persistent misconceptions can lead to misinterpretation of diagrams or to failing to recognise manipulated represented data, which can appear not only in commercials and other aspects of everyday life but also in scientific contexts.

This study is limited to the analysis of common mistakes when constructing line and bar diagrams in a biological context since these types of axis diagrams are particularly common in biology textbooks (Moore 1993; Roth et al. 1999) and therefore extremely important in biology classrooms.

Theoretical Background

Diagrams can be defined as depictional representations (Schnotz 2001). They involve an abstract congruence with the object represented. As such, non-spatial qualities such as import quotas and birth rates can be represented in a bar, line or circle diagram using spatial distances (Schnotz 2002). Quantitative relationships are represented using circle and axis diagrams (line, bar and scatter diagrams). Axis diagrams follow a conventional form and can, therefore, only be interpreted and constructed according to specific rules (Lachmayer 2008). This knowledge is a prerequisite for the construction of diagrams and will therefore be described in the following sections.

Line and Bar Diagrams as Examples of Axis Diagrams

Axis diagrams use a space delimited by two axes placed at a right angle. The horizontal axis is called the *abscissa* and the vertical axis is the *ordinate* (Schnotz 1994). Generally, the *independent variable* (IV) is assigned to the abscissa and the *dependent variable* (DV) to the ordinate. The axes of axis diagrams have a *scale* that divides them up into defined units of distance with the exception of the x axis of a bar diagram which does not necessarily have to be scaled. *Labelling the axes* serves to identify both variables, and a interval or ratio scaled variable must be additionally labelled with a unit of measurement that explains the distance between the values marked along the scale (Lachmayer 2008). A function f defines a relation between the values of the independent and dependent variable. Every value of the independent variable corresponds to one—and only one—value of the dependent variable. Accordingly, a “one-to-many relation” (vertical line) is not a function, while a “many-to-one relation” (horizontal line, e.g. $f(x)=5$) can be considered a constant function (Leinhardt et al. 1990). It is possible to plot multiple *data sets* in a line and bar diagram. The different data sets can be clearly distinguished in the diagram using different colours, shading or symbols explained in a *legend* (Lachmayer 2008). Additionally, two or more dependent variables can be depicted in an axis diagram using multiple ordinates.

Scale Type for Line and Bar Diagrams

In *line diagram*, the dependent and independent variables are interval or ratio scaled (Andreß 2001). The data points are connected by a line. It is important to consider whether the data for a variable are derived from an experiment with equal intervals between measurement dates (Kattmann 2006). If so, the line between the data points describes hypothetical values and must be distinguished from the real data points. This is referred to as an interpolation line (Kattmann 2006; Meyer 1988). Instead of only representing concrete data, a line diagram can also serve to illustrate general trends. Here no distinction is made between the plotted data points and the interpolation line (Lachmayer 2008). A vertical bar diagram should be used for discrete data (Kattmann 2006). The dependent variable is also interval or ratio scaled in a *vertical bar diagram*, but the independent variable can be scaled either nominally or ordinally (Köhler et al. 2002). Counter to the convention of assigning the independent variable to the abscissa and the dependent variable to the ordinate (Dytham 2003; Meyer 1988), the axes in a *horizontal bar diagram* are the other way around.

The Term "Mistake" and Common Mistakes with Diagrams

The term "mistake" has a range of meanings. Oser et al. (1999) present one definition favoured by didactics experts: a mistake is a discrepancy between a student's answer and the scientific theories previously presented in an instruction. Although mistakes have been assessed as negative and penalised for centuries (Weimer 1925), in recent years, our view of mistakes has become more constructivist studies on topics like 'learning from mistakes' have emerged (e.g. Althof 1999). We cannot simply focus on avoiding mistakes. Instead, we need to develop strategies for dealing with them when they happen (Harteis et al. 2006). These considerations—if and how we can learn from our mistakes and identifying the mistakes we can learn from—are increasingly the subject of research into education and learning (e.g. Brunner et al. 2006; Heinze 2004; Schwindt 2008; Seidel and Prenzel 2007; cited by Seifried et al. 2010). Negative knowledge may be one of the basic concepts shaping the processes of learning from mistakes (Gartmeier et al. 2008; Oser and Spychiger 2005). The negative knowledge theory posits that learning processes are initiated by negative experience. Here, negative knowledge offers a point of departure for acquiring positive knowledge and as such allows for the application of different learning strategies (Eraut 1994; Gartmeier et al. 2008; Parviainen and Eriksson 2006; cited by Wuttke and Seifried 2009). Today, many researchers describe mistakes as a constitutive feature of the learning process. As we assume that students can learn from their mistakes, it will be exceptionally important in the future to create teaching methods that consider students' mistakes (Seifried et al. 2010). In order to do so, we have to know the common mistakes of our pupils and of our tertiary students.

Previous studies have identified some common mistakes when primary and secondary students work with diagrams. The ability to select the proper type of diagram for the given data, for example, is not trivial. In Baker et al.'s (2001) study, less than 25 % of eighth and ninth grade students were able to select the proper diagram type when given four to choose from. Further, many students find it difficult to correctly assign variables to the proper axis and as such have trouble following this convention (Padilla et al. 1986). More than 10 % of the participating students for grade nine and ten in Lachmayer's (2008) study swapped the axes and assigned the variables to the opposite axes. In tasks in which participants were given four possible axes and had to choose the one that best suited the task at hand, the problems were correctly solved an average of 46 % of the time (Padilla et al. 1986). In addition, students may not be aware of the meaning of a connecting line in a line diagram. In a study by Kerslake (1981), for example, 46 % of the participating 15-year-old gave answers such as 'yes, I think this because it would be more accurate and look neater' or 'yes, because it is something you always do' when asked if the points plotted in a diagram should be connected (p. 124).

To better understand the implications for instruction not only in for high schools but also universities, it is worth investigating which mistakes are so persistent that tertiary science students still tend to make them. To answer this question, we sought to identify and analyse the common mistakes which occur in the different steps of the construction of diagrams.

The Analysis of Common Mistakes Using a Structural Model of Diagram Competence

Lachmayer et al. (2007) developed a competence model to assess students' skills in the use of diagrams. The primary aim of their study was to develop and empirically validate a structural model 'that describes the relevant competence structures and their relations, … required as a basis for both diagnosing and fostering graph competence in science classrooms' (p. 9). Based on a literature review of research on graph comprehension and cognitive psychology, three main components of diagram competence were distinguished: extraction of information from a diagram, construction of a diagram and integration of information from a diagram and a text (see Fig. 1). These three components were differentiated empirically as different abilities for both line diagrams and bar charts for students from ninth and tenth grade (Lachmayer 2008) and tertiary students (von Kotzebue and Nerdel 2012). Thus, attention to and promotion of these three skills is necessary during instruction.

In the following, only the one dimension of Lachmayer et al.'s model (2007) is reported. *Construction of the frame* and *data plotting* are postulated as the main categories of the dimension construction. To correctly construct a diagram frame, five steps are necessary: based on the given data, students have to select the appropriate diagram type and then assign the dependent and independent variables to the abscissa or the ordinate and label them with corresponding names and, if necessary, also with units. Next, a matching scale needs to be drawn, and if there is more than one dataset, a legend or a clear marking is necessary. After the construction of the frame, the given data can be plotted into the frame. Continuous data can be connected with a line to facilitate the identification of trends. The category "data plotting" may also include free sketching of trends, which data were, for example, just described vaguely in a text and not given as concrete data.

Study Aims

From these theoretical foundations, this study seeks to answer the following questions:

(1) What common mistakes do beginning tertiary science students make during each individual step when constructing a diagram?
(2) How often do they occur?

	Information extraction	**Construction**	
Identification	Recognise the illustrated relation	Selecting the right diagram type	**Construction of the frame**
	Assignment/classification of the variables to the axes	Assigning the variables to their axes	
		Labelling the axes	
	Assignment of the data series to the symbols ('legends')	Drawing the scale	
	Note the scale range	Creating the legend	
Off-reading	1. Order: read a numeric value	Plotting the data points	**Data plotting**
	2. Order: compare two values or recognising a trend (qualitative/quantitative)	Sketching a connecting line between the data points or free sketching a trend line[a]	
	3. Order: compare of multiple values or compare trends (qualitative/quantitative)	Freehand drawing of multiple trends[a]	
	Extrapolate/predict		
Integration			

Fig. 1 Structural model of diagram competence (Lachmayer et al. 2007). [a]Characterised by operations relating only to line diagrams

Study Design

Research Participants

There were 437 first-year tertiary science students who took part in this study. For these students, the start of their studies marks the level of *diagram competence* they had achieved at the end of high school. In addition, it is their starting point for further development of this competence at a university level. Thus, it makes sense to assess their ability to construct diagrams when they leave school, since this ability is an objective in the German curricula, and in the biology final exams, there are almost always tasks that require this ability. Two questionnaires were used to gather data. The first contained diagram exercises involving photosynthesis (n=218) and the second involved ecology (n=219). The youngest participant was 17 and the oldest 30 years of age. The mean age of the students was 23.5 years (SD=4.19 years). Of the participants, 56 % were female.

Questionnaires

The research instrument used in this study determined students' ability to solve contextualised diagram problems involving photosynthesis or ecology. These were systematically evaluated to identify the common mistakes that emerged.

Characteristics and Requirements of the Tasks All four tasks asked students to construct a diagram which involved filtering the relevant data from a previous assignment. The pairs of values required to construct the diagram were either presented in a value table or had to be extrapolated from a diagram and corresponding text. In other words, no explicit additional knowledge was required to complete the task. The materials present contained all the biological information relevant to the solution. As such, solving the diagram tasks required a methodological understanding of how to construct diagrams and the ability to integrate information from different sources (Lachmayer 2008; von Kotzebue and Nerdel 2012). The *time of day* and *sample taking* tasks contained an additional question: participants were asked to explain their rationale for assigning the particular values to the axes in the diagrams they drew. Table 1 summarises each of the tasks.

The four diagram tasks are presented below together with the individual problems and the recommended solutions.

Task 1 Time of Day: Construction of a diagram based on a value table that presents the carbon dioxide ratio depending on time of day. The unit of the DV is given in the text, and the values are positive and negative decimals (Fig. 2).

Task 2 Water Depth: Construction of a diagram based on visual and textual information that presents the irradiance depending on water depth. The unit of the IV as well as the DV are given in a diagram, and the values are positive integers (Fig. 3).

Task 3 Sample Taking: Construction of a diagram based on a value table that presents the nitrate concentration depending on the date of sampling. The unit of the IV is given in a table, and the values are certain days. The unit of the DV is given in the text, and the values are positive integers (Fig. 4).

Table 1 Analysis of the diagram tasks based on their formal characteristics

	Time of day	Water depth	Sample taking	Fish species
Context	Photosynthesis	Photosynthesis	Ecology	Ecology
Values derived from	Value table	Diagram	Value table	Diagram
Independent variable (IV) and type of scale	Time of day in hours (interval scale)	Water depth in metres (ratio scale)	Date of sampling (ordinal scale[a])	Fish species (categorical variable)
Dependent variable (DV) and type of scale	Carbon dioxide ratio in nanomoles per gram per hour (ratio scale)	Light intensity in percentage (ratio scale)	Nitrate concentration in milligrammes per litre (ratio scale)	Survival rate in percentage (ratio scale)
Number of data sets	2	1	2	1

[a] Although the literature indicates that an interval scale is preferable (Götze and Bloech 2002; Zimmermann and Gutsche 1991) the ordinal scale should be used because the distance between two sampling dates is not always the same. There are 28 days between February 15 and March 15 and 31 days between May 15 and June 15, for example

Task 4 Fish Species: Construction of a diagram based on visual and textual information that presents the survival rate depending on fish species. The unit of the DV is given in a diagram, and the values are positive decimals (Fig. 5).

Evaluation Method

Lachmayer et al.'s (2007) structural model of diagram competence served as the theoretical foundation for the deductive category system used to analyse the participants' solutions. The model describes aspects that pertain to the construction of diagrams. Eight categories were used, as described below. This theoretical category system was then expanded by inductive categories based on the data sets. Since we were interested in the entire qualitative breadth of

The carbon dioxide ratio of two plant species is represented in the table below. The values are given in nmol of carbon dioxide per gram of plant weight and hour. Positive values denote an increase, negative ones a drop in CO_2.

Time	0:00	6:00	12:00	18:00
Encyclica	1	5	0.5	-1
Catasetum	-3	-3	6	3

Task: *Use the values from the table to construct a complete diagram that illustrates the development of carbon dioxide ratio over time in both plant species. Do not forget to include a legend.*

Possible solution:

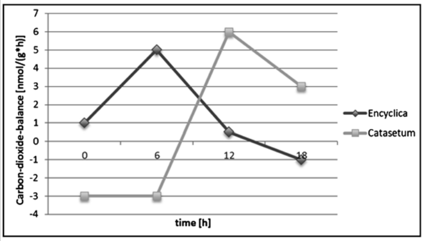
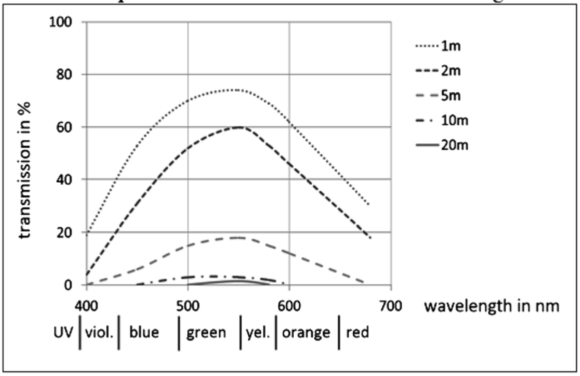


Fig. 2 Task (*left*) and possible solution (*right*): 'Carbon dioxide ratio depending on time /time of day' (All tasks and labels have been translated into English but were German in the questionnaire.) (Adapted version of a task from the advanced course biology (Leistungskurs Biologie 2005, IV/3) of the Bavarian Abitur (a German schoolleaving exam.) see in Abitur 2009: Prüfungsaufgaben mit Lösungen. Biologie Gymnasium Bayern (2010))

The deeper sunlight penetrates into the depths of the ocean, the more light is absorbed by water molecules in different amounts depending on wavelength. First look at the diagram below that shows the intensity of light as a percentage of the rays that hit the water's surface at different depths in the ocean as a function of the light's wavelength.



Task*: Then create a new, completely labelled diagram that shows irradiance as a function of water depth. Please note that the graph should only be plotted for a wavelength of 500nm. Begin by setting up a value table by extracting pairs of values from the graph below.*

Possible solution:

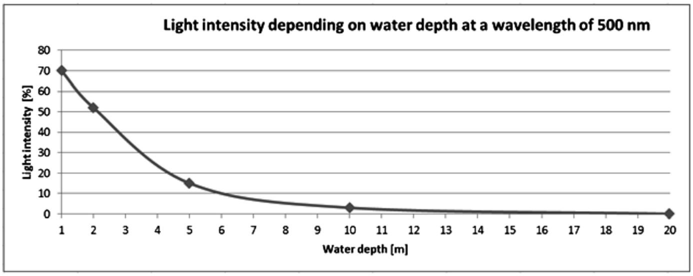


Fig. 3 Task (*above*) and possible solution (*below*): 'Irradiation depending on water depth' (adapted version of a task from the advanced course biology (Leistungskurs Biologie 2006, II/2) of the Bavarian Abitur (a German school-leaving exam) see in Abitur 2009: Prüfungsaufgaben mit Lösungen. Biologie Gymnasium Bayern (2010))

solutions, wrong answers were divided into new categories. This allowed us to draw detailed conclusions from students' processes when constructing diagrams. We then quantified the different types of solutions and common mistakes identified so that we could find out what the findings might mean. The number of times a given task was completed was also considered. Five percent of the data were coded twice to examine the consistent evaluation of the task categories. There was agreement of 98.5 % between the three raters. Thus, there was a very high degree of concordance among the judges. Member validation was used when the cases were controversial. The results of these informant feedbacks were specified in coding manuals.

Deductive Category System

The deductive category system used in this study comprises the following eight categories:

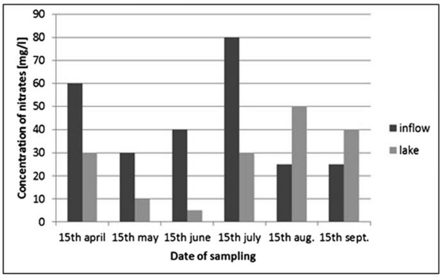
Category 1 Selecting the correct diagram type
Category 2a Assigning the variables to the axes
Category 2b Rationale behind the assignment of the axes
Category 3 Labelling the axes

The nitrate concentration [mg/l] of a lake and inflow were sampled at regular intervals. Both the lake and the inflow are surrounded by intensively used agricultural fields, so we can presume that the nitrate contamination of the lake via the inflow varies widely. The nitrate concentrations measured in the lake and inflow are presented in the table below:

Date of sampling	inflow	lake
15 April	60	30
15 May	30	10
15 June	40	5
15 July	80	30
15 August	25	50
15 September	25	40

Task*: Using values from the table, construct a diagram that reflects the relation between nitrate concentration and sampling date.*

Possible solutions:



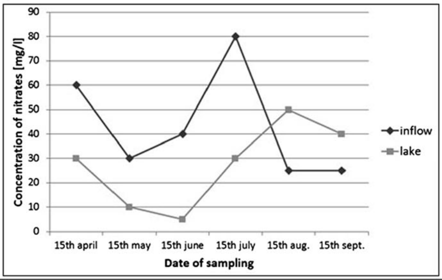
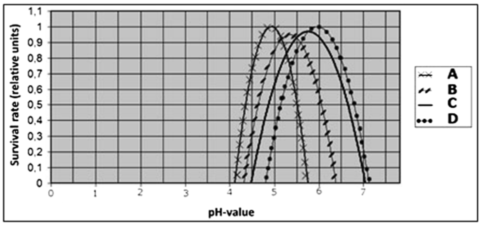


Fig. 4 Task (*left*) and possible solutions (*right*): 'Nitrate concentration depending on the date of sampling (sample taking)' (adapted version of a task from the advanced course biologyAbitur 2009: Prüfungsaufgaben mit Lösungen. Biologie Gymnasium Bayern (2010)

Organisms that live in the water have different tolerances to water pH. First look at the diagram below that depicts the survival rate of four fish species A, B, C, and D depending on the pH of the water.



Task*: Construct a new, completely labelled diagram that depicts the relation between the survival rate and species at a pH of 5.0. Extract the data you need from the diagram.*

Solution:

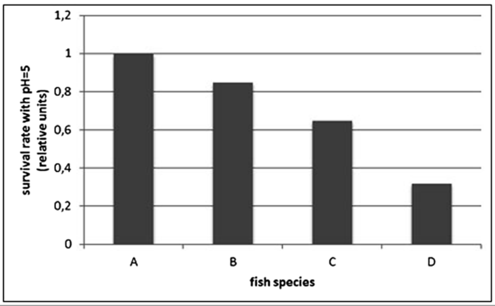


Fig. 5 Task (*left*) and possible solution (*right*): 'Survival rate depending on fish species (fish species)'

Category 4 Drawing the scale
Category 5 Creating the legend
Category 6 Plotting the data points
Category 7 Sketching a connecting line between the data points

According to the structural model of diagram competence, categories 1 through 5 (except for 2b) correspond to the 'construction of the frame' subcomponent (Lachmayer 2008). Category 2b *rationale behind the assignment of the axes* was added specifically for the purpose of this study to determine if students just intuitively choose the correct assignment of the axes or because of knowledge of the convention or other reasons they can explain. Categories 6 and 7 are part of the 'data plotting' subcomponent Lachmayer's, though category 7 does not correspond exactly to this category, which was called *sketching a connecting line between points or freehand drawing a trend line*. A trend or interpolation line between two values is a model that serves to predict possible measured data between these two data points. As a model is not right or wrong, the line can only be more or less suitable to explain data, and implies that there are further measured values between the two points which can be approximately represented as a line. If further measurements do not support this model, new lines have to be drawn between the data points which are better suited as a model. Furthermore, the category system does not include the *freehand drawing of multiple trends* category since these skills were not necessary to solve the diagram tasks set in this study. This skill is necessary if the trend is only described in a text, and no exact data are given, which did not occur in any of the four tasks.

Results

The respective subcategories for each individual category are presented below and illustrated by examples. In addition, there are frequency analyses for the four tasks. The tasks were completed at the following rate of frequency: time of day 88 %, water depth 74 %, sample taking 93 % and fish species 82 %. Overall, the photosynthesis task was completed by n=218 and the ecology questionnaire by n=219. The percentages given below refer to these numbers.

Category 1: Selecting the Correct Diagram Type

An analysis of the data revealed the following diagram types that were used: line diagram, vertical bar diagram with no set length; histogram; horizontal bar diagram; horizontal bar diagram with no set length; scatter diagram; combination of line and vertical bar diagram; and missing. In 8 to 31 % of the cases, the solution did not offer a clear diagram type (see Table 2). In addition to diagram types that could not be categorised, a line diagram was almost exclusively selected for all tasks except the fish species task. Here, the greatest variation in the choice of the diagram type occurred: 30 % selected a vertical bar diagram, 25 % a line diagram,

Table 2 Frequency of the cases where no clear diagram type could be identified; n=218 (tasks with photosynthesis context: time of day; water depth), n=219 (tasks with ecology context: sample taking; fish species)

	Time of day (%)	Water depth (%)	Sample taking (%)	Fish species (%)
No clear diagram type	15	31	8	18
Line diagram	84	67	80	25

Frequencies (%) were rounded to integers; '0', for example, includes values from 0.0 up to and including 0.5

21 % a scatter diagram, 3 % a combination of line and vertical bar diagram, and 2 % a histogram. This list does not include those diagram types with a frequency of no more than 1 %. The recommended diagram type for the tasks time of day and water depth is a line diagram; for the sample taking task, the preferred type is a bar chart, because of the unequal intervals between measurement dates, but a line or a scatter diagram is not wrong. A bar chart or even a scatter diagram is recommended for the fish species task.

Category 2a: Assigning the Variables to the Axes

Almost every possible variation in assigning the variables to the axes was observed. The abscissa and ordinate were reversed, the data sets were written on the axes, a variable was used as the data set and individual variables were completely left out. Figure 5 shows examples of the two most common mistakes. “Mistake 1” is a reversal of the dependent and independent variable and “Mistake 2” involves assigning the individual data to the axes and using the data set as the dependent or independent variable.

For the water depth and fish species tasks, the most common incorrect assignment of the variables to the axes was a swapping of the axes (see Fig. 6, mistake 1). The DV was assigned to the ordinate and the IV to the abscissa 3 % of the time for the water depth task and 6 % for the fish species task. For the sample taking task, the individual data sets were assigned to the axes 9 % of the time and 8 % for the fish species task. The dependent or independent variable was then used as the data set (see Fig. 6, mistake 2). The remaining incorrect assignments occurred with pretty much the same frequency among the different tasks, and none occurred more than 2 % of the time. Table 3 presents the frequency of the correct, incorrect and missing assignment of the variables to the axes.

Category 2b: Rationale Behind the Assignment of the Axes

Participants were asked to explain their rationale for the assignment of the variables to the axes for the time of day and sample taking tasks. Twenty-five percent provided a correct reason for the sample taking task, such as ‘the nitrate concentration of the inflow and the lake depends on the month → higher concentration due to the more intensive use of the agricultural fields surrounding the inflow and lake in certain months’. Forty-seven percent provided a vague explanation such as ‘this makes it easy to see how the nitrate concentration changes over time’. Around 28 % of the time, no answer or an incorrect answer—such as ‘there are two y values (two nitrate values) for every x value. It would not work the other way around. One y value

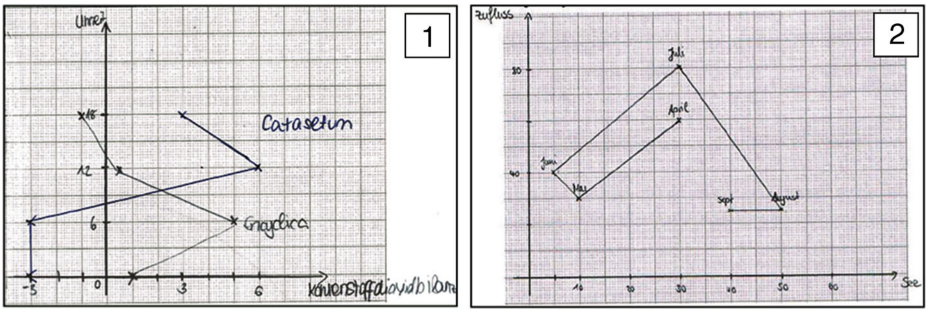


Fig. 6 Solutions for 2a: assigning the variables to the axis category (translation of the labels: **1** time of day (DV) and carbon dioxide ratio (IV); **2** inflow (DV) and lake (IV))

Table 3 Frequency of correct, incorrect and missing assignment of the variables to the axes; $n=192$ (time of day), $n=161$ (water depth), $n=204$ (sample taking), $n=180$ (fish species)

	Time of day (%)	Water depth (%)	Sample taking (%)	Fish species (%)
Correct assignment of the variables to the axes	86	67	82	69
Incorrect assignment of the variables to the axes	2	4	11	16
Missing	12	29	7	15

Frequencies (%) were rounded to integers

could not be assigned to two x values'—was given. For the time of day task, around 31 % of participants provided a correct rationale, such as 'time is the constant factor for both plant samplings'. Thirty-three percent gave a vague answer and 36 % no or an incorrect answer.

Category 3: Labelling the Axes

The labelling of the axes was divided into the following subcategories:

- 'Everything correct': both the labels for the axes and the unit of measurement were present in the correct form for both the independent variable and the dependent variable, e.g. the correct labelling for the time of day task is carbon dioxide ratio [nmol/(g×h)] on the DV and time (h) or time of day (h) on the IV.
- 'Partially incorrect': a mistake was made either in the labelling of the axes and/or in the unit for the independent variable and/or the dependent variable (at least one mistake occurred), e.g. for the time of day task is carbon dioxide ratio on the DV and time (h) on the IV.
- 'Everything missing': the labelling of the axes and the unit were not present in the correct form for both the independent variable and the dependent variable.

Independent of the subcategories listed above, the frequency with which the two axes were labelled 'x' and 'y' was also recorded. The respective frequencies are presented in Table 4.

Category 4: Drawing the Scale

The analysis of the scaling identified the percentage of responses that were either *correct*, *missing* or *incorrect*. This was done for both the dependent and independent variables. The frequency analysis is presented in Fig. 7.

Table 4 Frequency of the subcategories for the variable labelling of the axes; $n=192$ (time of day), $n=161$ (water depth), $n=204$ (sample taking), $n=180$ (fish species)

	Time of day (%)	Water depth (%)	Sample taking (%)	Fish species (%)
Everything correct	2	29	5	11
Partially incorrect	79	43	79	70
Everything missing	17	28	15	20
Axes labelled 'x' and 'y'	9	9	9	5

Frequencies (%) were rounded up to integers

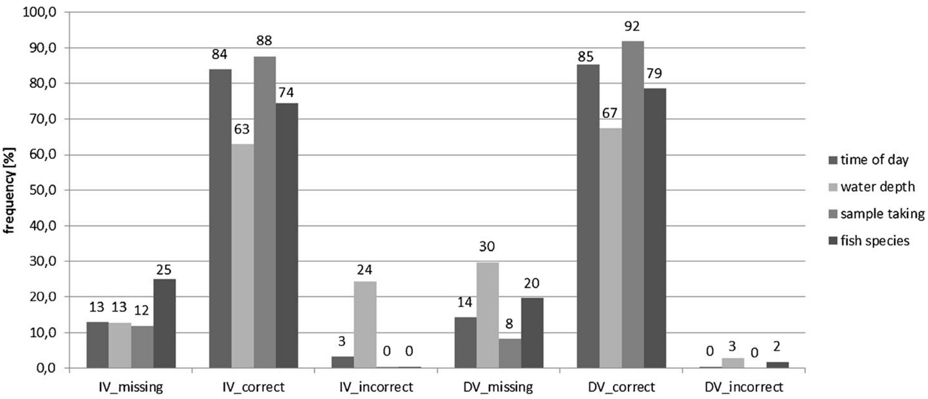


Fig. 7 Frequency (%) of 'drawing the scale'; n=192 (time of day), n=161 (water depth), n=204 (sample taking), n=180 (fish species). Frequencies (%) were rounded to integers

For the water depth task, the following was observed with the independent variable in the incorrect category: in 5 % of all cases, the number 20 was omitted in the scaling of the abscissa, and in 9 % of all cases, the numbers 1, 2, 5, 10 and 20 were drawn at even intervals along the scale. With respect to the independent variables for the time of day task, it was observed that in 2 % of all cases, the positive numbers and the negative numbers were differently scaled, and 2 % of the time, the negative numbers were left off in the scaling. Examples are shown in Fig. 8.

Category 5: Creating the Legend

In the line diagrams with two data sets (time of day and sample taking), the data sets were labelled with a correct legend (e.g. with shading or symbols) in 38 % of cases. A legend was missing 27 % of the time, and roughly 28 % of the time, the data set was directly labelled on the graph in the diagram. About 7 % of the time, the legend was incorrect in that either markings in the text or table served as the label for the graph, abbreviations were used, or only one data set was labelled.

For vertical bar diagrams for the fish species task, a correct legend was present 18 % of the time, absent 63 % of the time and partially incorrect 20 % of the time.

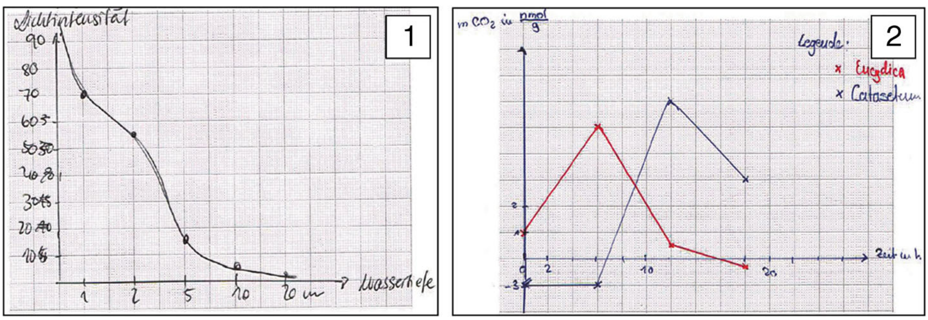


Fig. 8 Examples of solutions from the incorrect subcategory (translation: **1** light intensity (DV) and water depth (IV); **2** CO_2 in nanomoles per gramme (DV) and time in hours (IV))

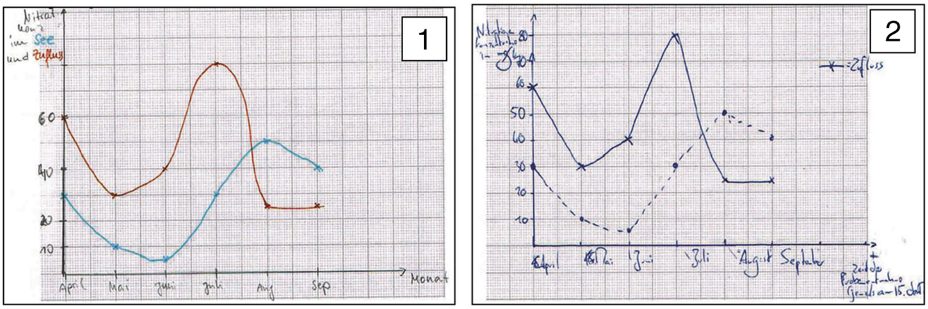


Fig. 9 Examples for 'creating the legend': **1** Written along the axes (Translation: nitrate concentration in lake and inflow (DV) and month (IV)); **2** only one data set labelled (translation: nitrate concentration in milligrammes per litre (DV), time of sampling (on the 15th of the month) (IV), and inflow (legend))

The water depth task required students to construct a diagram using just one data set. Here, only 5 % of the participants' diagrams were labelled with a proper legend, 88 % had none at all and 7 % a partially incorrect one. Figure 9 shows examples of legends drawn partially incorrectly.

Table 5 Frequencies of the values plotted; $n=192$ (time of day), $n=161$ (water depth), $n=204$ (sample taking), and $n=180$ (fish species)

	Time of day (%)	Water depth (%)	Sample taking (%)	Fish species (%)
All pairs of values correct	72	48	81	75
At least one pair of values plotted incorrectly	12	16	10	4
No values correct	16	36	9	21

Frequencies (%) were rounded to integers; '0', for example, includes values from 0.0 up to and including 0.5

Category 6: Plotting the Data Points

The frequency of the correct plotting of the pairs of values differed greatly from task to task as shown in Table 5. The study distinguishes between three responses for plotting data points: the

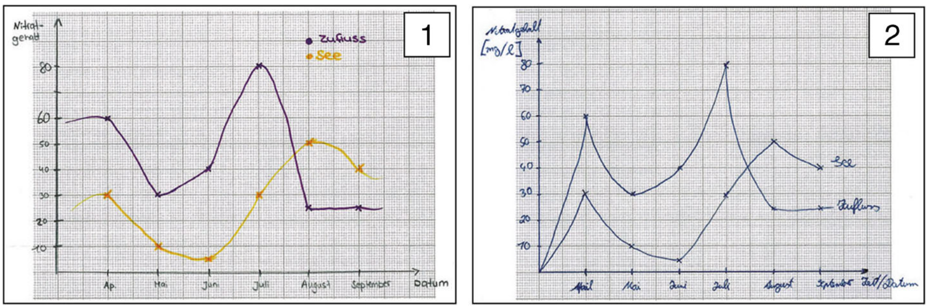


Fig. 10 Examples of 'sketching a connecting line between the pairs of values': **1** connecting line drawn beyond the data; **2** connecting line linked to the zero point (translation: **1** nitrate concentration (DV), date (IV), and inflow and lake (legend); **2** nitrate concentration in milligrammes per litre (DV), time/date (IV), and inflow and lake (legend))

Table 6 Frequency of the subcategories for 'sketching a connecting line between the pairs of values'; n=183 (time of day), n=145 (water depth), n=174 (sample taking), n=54 (fish species)

	Time of day (%)	Water depth (%)	Sample taking (%)	Fish species (%)
Drawn beyond the data	14	36	10	30
Included zero point	3	1	2	0

Frequencies (%) were rounded to integers

correct plotting of all pairs of values, at least one incorrectly plotted pair of values, and no correctly plotted pair of values.

Category 7: Sketching a Connecting Line Between the Pairs of Values

This category only refers to attempted solutions in which a line diagram was used even if it represented an incorrect solution. An analysis of the data for the 'sketching a connecting line between the pairs of values' category resulted in two subcategories: line drawn beyond the data and zero point included. Figure 10 shows some examples of these subcategories, and Table 6 shows the frequency analysis of these examples.

In addition to the subcategories described above, the data points were also incorrectly connected (values left out or too many included) in a few individual cases.

Discussion

Selecting the Correct Diagram Type

Participants seemed most familiar with line diagrams. This may be attributable to the fact that this is the type most commonly used in educational materials. In two cases, the time of day and water depth tasks, this was also the correct solution. For the sample taking task, however, instead of using the recommended bar chart type, large proportion of participants drew a line diagram. As such, our results support the hypothesis that students tend to use line diagrams whenever a variable associated with time is present, such as the 'date of sampling' variable here. This raises the question whether this was a conscious decision and if students consciously ignored the unequal intervals between the measurement dates (April 15, May 15, etc.) to clearly represent the development over time. Another explanation for this phenomenon could be that students did not recognise the unequal intervals between the sampling dates and assumed a continuous time variable. The real values measured can only be linked by a line if the intervals between measurement dates are equal. This line then is characterised as interpolation and as such represents hypothetically measured values. If only discontinuous measurements are available, then a bar chart is the preferred form in most cases (Kattmann 2006). For the fish species task, the only task with a categorical independent variable, it was surprising to note that students used all types of diagrams. Although a bar chart or more uncommon scatter diagram would have been correct solutions, a quarter of all test subjects selected a line diagram. To solve this task, students had to first extrapolate the pairs of values from a given line diagram. One possible reason for the high frequency of line diagrams might be that many test subjects concluded that the new diagram they needed to draw would have a linear relation because the original diagram did.

Only around one third of all students selected a vertical bar diagram for this task. Around one fifth of the solutions constructed a scatter diagram. A possible interpretation here is that the test subjects could not decide between a bar and a line diagram and therefore decided not to 'process' the values any further.

Lachmayer (2008), who completed a study using diagrams in a biological context with students from grades nine and ten, also observed that a line diagram was used instead of a bar chart around 10 % of the time depending on the task. According to Lachmayer, this might be attributed to the fact that some of the students were not aware of the interpolative character of a line (Kerslake 1981) and that line diagrams are often used for better readability when presenting categorical data in schools and in science (e.g. typical representation of an interaction diagram for a two-factor variance analysis, see Bortz and Döring 2006).

Assigning the Variables to the Axes

Although the variables were not often incorrectly assigned to the axes, a wide range of incorrect assignments was identified. The most common mistake was that the independent variable and the dependent variable were assigned to the opposite axes to those dictated by convention. In Lachmayer's (2008) study, this mistake occurred 10–23 % of the time and therefore with somewhat greater frequency than in this study. In addition, when students had to choose the correct axes from four possibilities, only about 46 % could select the right answer (Padilla et al. 1986). With this type of mistake, however, it is important to note that in some circumstances, the principle of the dependence of the variables on one another may have been understood in general but that the convention for how variables are assigned to axes might be unfamiliar. Features of the task, such as the number of data sets or whether a variable with a time-like component is present, might influence the frequency of the correct assignment of variables to the axes. Findings from the current study show that the tasks that required presenting two data sets and contained a time-like variable were solved correctly more often than tasks that did not include these characteristics. A possible explanation could be that a time-like variable is often automatically assigned to the IV, even though this is not always correct. Furthermore, two data sets may be less likely to be confused with the DV or the IV because they attract attention as something similar or something to compare with each other.

Rationale Behind the Assignment of the Axes

The frequency of very vague answers, such as 'the diagram is easier to read this way', given as the rationale for the assignment of the axes and those that were categorised as incorrect, was striking. Clearly, wrong answers were given less often, such as 'x is always the time axis'. While this is true in many cases, time is not *always* assigned to the abscissa. Another reason defined as 'wrong' was 'it is not possible to have two x values per each y value'. This may express an effort to achieve a 'one-to-one correspondence', according to which every x value in a definition set may only correspond to one y value from a value set. This one-to-one correspondence goes hand in hand with the definition of a function (Leinhardt et al. 1990) and is often introduced in school as an element of the 'linear function' unit. However, the statement cited above is incorrect as it relates to the one-to-one correspondence just explained. As it stands, the assertion that '2 x values are not possible per y value' is a wrong conclusion. According to Vinner (1983), this type of 'symmetrical' reversal of the statement is seen as an implicit explanation of the correctness of both.

Labelling the Axes

A number of errors regarding content were observed in the labelling of the axes. Sometimes an abbreviation was used as a label for an axis (e.g. instead of ‘carbon dioxide concentration’ or ‘CO_2 concentration’ just ‘CO_2’), or the axes were labelled completely incorrectly (e.g. instead of ‘CO_2 concentration’, ‘plant growth’). On average, more than half of the tertiary science students had just partly correct labelling of the axes. Thus, there seems be a great need for science instruction that gives students training in the correct labelling of the axes.

This study identified one previously undescribed common mistake relating to labelling the axes of diagrams. It is the conventional approach taken from mathematics of labelling the axes with ‘x’ and ‘y’. Although labelling the axes in this manner is both necessary and desirable in mathematics class in most cases, for diagrams used in a scientific context, it is not necessary since, here, relations between defined and named scientific variables are represented graphically. In this study, this common mistake appeared in around 11 % of the cases. Apparently, even higher-education students are still so fixated on this mathematical convention that they apply it to non-mathematical contexts.

Drawing the Scale

What was striking in this study was the fact that the independent variable ‘water depth’ in the water depth task was very often scaled incorrectly. We determined that correct scaling depended on the complexity of the mathematical operation: the more complex the mathematical operation was, e.g. no obvious smallest multiple and a coordinate system that seemed too small (16-cm width in the coordinate system for 20 m of water depth), the less frequently the axes of the diagram were correctly scaled, such as marking 1, 2, 5, 10 and 20 at the same intervals along the scale. This mistake has also been observed in other studies (e.g. Wavering 1989).

Creating a Legend

The ‘creating a legend’ category can be viewed critically since there seems to be no clearly defined conventions for correctly constructing a legend (Cleveland 1994). Here, the category was considered to have been solved correctly if an extra identification of the data sets was visible apart from the graph. It is hard to define ‘labelled directly on the graph’ as ‘wrong’, since this seems to be a common way of identifying data sets in scientific literature. As such, students identified the graphs in keeping with a ‘common sense’ approach used by the scientific community and not according to a definition or rule. In contrast, the remaining subcategories, such as ‘markings in the text or table’, seemed to be less common approaches. These are more difficult to read and must therefore be considered at least partially incorrect. Asking participants to create a legend for just one data set, as would be the case for the water depth and fish species tasks, should also be viewed as kind of problematic because the content of these diagrams could also be understood without a legend.

Sketching a Connecting Line Between Value Pairs

The common mistake drawing the connecting line beyond the data occurred much less frequently for tasks where the values were given in a value table. When students were forced to extrapolate the pairs of value from a diagram, however, they tended to draw past the pairs included in the diagram. For the water depth task, this extrapolation of the connecting line between the data points could be logically explained by the content. The diagram given allows for the assumption that the irradiation at a wavelength of 500 nm would be 100 % at the hypothetically assumed water depth of 0 and converge on 0 % at a hypothetical water depth of more than 20 m. It was evident, however, that some higher-education students are unaware that the line that connects the plotted data points cannot be extended to the origin if no data point is located at the origin and that the line ends with the last pair of values measured since this line represents the presence of measured data.

Conclusion

This study identified some deficits in young higher-education students constructing diagrams, some of the deficits having previously been identified in middle school students. Additionally, mistakes based on the specific context of the tasks set, such as labelling the axes and the tendency to identify the abscissa with an *x* and the ordinate with a *y*, were observed. The beginning tertiary science students had difficulties in all eight analysed categories, which represented necessary steps to constructing a complete diagram. In particular several misconceptions and mistakes seem to persist from school right through to university, like the difficulty in selecting the right type of diagram for a given set of data. The frequent selection of a line diagram as well as the connecting of the pair of values related to this preference resulted in an incorrect interpretation of the context.

Although most of the students could correctly assign the dependent and independent variables to the axes, very few could justify their choice. One consequence of these difficulties could be that the advantages diagrams offer as teaching and learning tools, particularly in science, cannot be maximized. Advantages include the illustrative and concise presentation of complex research results and that diagrams can serve as a thinking tool in the context of a scientific inquiry and thus support the formulation and testing of hypotheses and the interpretation of research results (Kozma et al. 2000). Thus, there is great need for suitable classroom approaches that teach students how to interact with diagrams and the continual implementation of these methods in science classes.

Identifying students' mistakes and relating them to common alternative conceptions is considered an essential prerequisite for successful instruction (Schumacher 2008). Recent studies in science education, e.g. the COACTIV study (Krauss et al. 2011), have systematically analysed teacher's professional knowledge and provided additional empirical findings that support the idea that teachers must be aware of the typical ways students process content so they can adapt their instruction accordingly (Kunter et al. 2011). Problems and mistakes are particularly effective in revealing a problem solver's tacit knowledge and are often essential to rendering cognitive processes visible (Malle 1993; Matz 1982). The conventions for diagrams should be addressed in both higher-education didactics and teacher training as well as the requirements for the construction of diagrams in a biological context. Data from this study are indicative of the types of problems future teachers will face when teaching the correct use of diagrams. These can serve as example which can be discussed in courses which focus on dealing with diagrams. Conceptual change methodologies may be an appropriate intervention to help students develop the skills to correctly construct and interpret diagrams and overcome these common mistakes (von Kotzebue, 2014). To sum up, the findings of this study will hopefully help to enhance the further development of the didactic training of teachers to accurately construct scientific diagrams.

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