Chapter 7

The Zoom Map: Explaining Complex Biological Phenomena by Drawing Connections Between and in Levels of Organization

Niklas Schneeweiß and Harald Gropengießer

7.1 Introduction

Understanding and explaining complex biological phenomena such as the results of climate change or evolution requires students to think systemically. However, systems thinking—namely, relating concepts to the right level of organization or adequately interrelating concepts across levels of organization—is difficult for students. To address this issue, science educators have proposed to apply learning and teaching strategies such as the yo-yo (Knippels, 2002; Knippels et al., 2005) and tools that foster understanding, such as the concept map (Novak, 1990). A characteristic of yo-yo learning environments is addressing and changing the levels of organization.

Nonetheless, teachers can and should encourage learners to interact with the levels. We propose the zoom map as a useful tool to reflect on levels of organization and explain complex biological phenomena. By making levels of organization explicit and incorporating the idea of zooming in and out of a phenomenon, we intend to guide students' explanations across the levels of organization. This chapter discusses how the zoom map encourages learners to reason on different levels of organization.

To begin with, we briefly outline the difficulties of biological complexity with a focus on the role of the levels of organization. After that, we concentrate on biological complexity both from the scientists' and students' perspectives to derive teaching-guidelines from the educators' perspective. Further on, we explain how the zoom map relates to these guidelines and can help cope with biological complexity. Following the description of our methods, we discuss evidence from teaching

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interviews. We conclude by presenting our research's implications for teaching biology.

7.2 What Makes Biological Explanations Complex? The Perspective of Scientists

7.2.1 *Characteristics of Biological Explanations*

Biologists, chemists, physicists, and other science experts originally performed research to construct the explanations of scientific phenomena of the world around us. Most sciences started with observing and describing phenomena. A currently more advanced science such as biology developed the art of explanation and prediction. An explanation needs an explanandum, that is, something to be explained, and an explanans, by which it is explained. The explanans consists of antecedents, namely initial or boundary conditions that, together with general laws or regularities, result in causal explanations (Hempel & Oppenheim, 1948).

According to Mayr (1961) explanations in biology fall into two forms of explanantia: proximate causes (namely, physiological mechanisms) and ultimate causes—namely, evolutionary mechanisms that explain the existence of a specific trait through variation in a population and non-random survival in a given environment. This distinction has been further elaborated and complemented, but is still regarded as vital (e.g. Laland et al., 2011). Furthermore, the distinction has proved its usefulness in selecting conceptual content for biology curricula (Carvalho et al., 2020). The explanandum in biology is, in most cases, a phenomenon that has no straightforward explanation, unlike the movement of a billiard ball. In biology, the explanans may be structured as a causal chain, but, more often, it is like a net or even a felt, and, as if that were not enough, it runs over several levels of organization.Today, it is commonly accepted that "complexity is endemic in biology" (Mitchell, 2012, p. xiii) because the latter "is constituted by […] multilevel […] systems." We assume complexity when we observe a phenomenon that emerges from entities with specific properties that interact. A system can be described as complex (Dauer & Dauer, 2016; Eilam, 2012; Mitchell, 2012) if it:

- is open.
- is structured into multiple levels of organization.
- has many entities.
- presents interaction of entities within and across levels of organization.
- is influenced by the entities' behavior and.
- has emergent properties.

7.2.2 *A Plethora of Biological Levels*

We have introduced what makes biological explanation complex. Arguably, the multiple levels of organization significantly contribute to the complexity of biology. To complicate matters, albeit the omnipresent usage of the term levels of organization in biology and biology education, the term is not as clear as its prevalence might suggest. Even fundamental questions such as, "Which are the levels of organization" are not yet definitely answered (Eronen & Brooks, 2018; Schneeweiß & Gropengießer, 2019). As a first step towards a new consensus on levels, we conducted a literature review on the levels of organization in the fields of biology and biology education to shed light on the diversity of levels. The review (Schneeweiß & Gropengießer, 2019) revealed 20 different levels of organization and some more synonyms (Fig. 7.1).

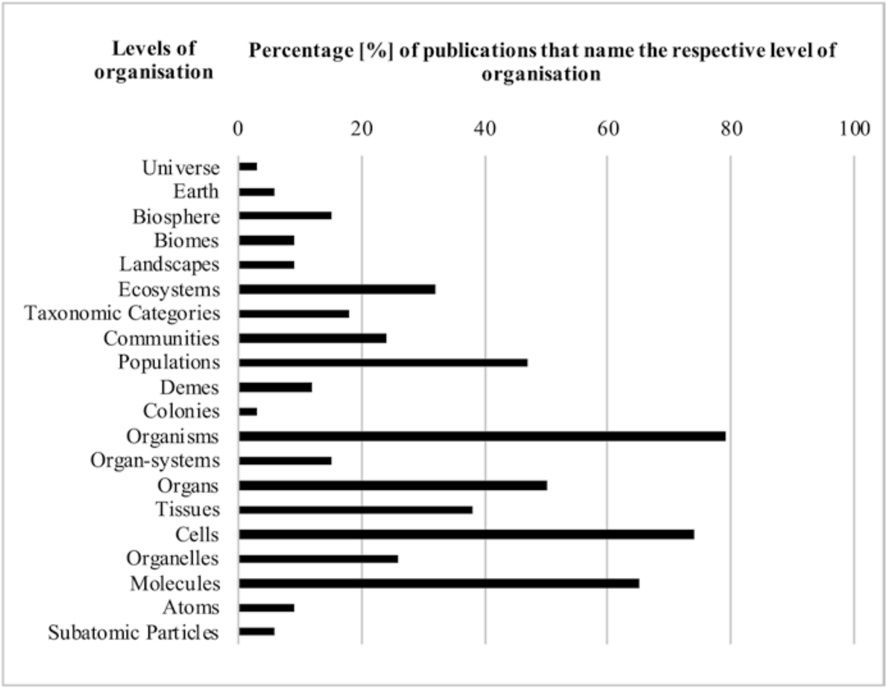

Fig. 7.1 Coding results for individual levels of organization explicitly named in biology and biology education journal articles ($N = 36$). The percentage refers to the number of papers that name the respective level at least once in relation to the total number of papers

7.2.3 *Organizing the Levels of Biological Organization*

Our review further revealed that levels of organization can be formed, ordered, and related through different relationships—mainly, coevolutionary, matter-energy, and physiological relationships that can be ordered in a system of levels (MacMahon et al., 1978; Schneeweiß & Gropengießer, 2019; Fig. 7.2). Picket et al. (2007) point out that each level has different facets for example behaviour or appearance. Different biological research traditions may focus on distinct facets.

7.2.4 *Comparing the Levels of Scientific Disciplines*

A look at disciplines such as physics and chemistry suggests that things seem to be less complex, at least regarding the levels. Physicists use a scale of powers of ten to place their objects of study. Philosophers with an evolutionary epistemological point of view hold that our cognitive system is adapted to a world of medium dimensions—a world that we can perceive and interact with. Vollmer (1984) calls this section of the real world the mesocosm. Things that are smaller as the breadth of a hair or larger than the distance to the horizon are hard to understand, as they belong to the microcosm or macrocosm, respectively (Niebert & Gropengiesser, 2015). Chemists use the three levels of microscopic particle, nanoparticle, and substance (submacro, macro, and an extra-symbolic level; Johnstone, 1991). Even if we consider the recent discussion about a nano-level in chemistry, there is no comparison with the multitude of levels in biology (Fig. 7.3).

The shown complexity by levels in biology is challenging, this applies all the more as the levels of organisation—especially in their non-branched version—may invoke the misleading idea that this hierarchy is strictly based on the size of an observed object. But a small log on the forest floor may be regarded as an ecosystem as well as it is part of a large forest community. This led to the construction of an alternative representation, particularly suitable for ecological research (Pickett et al., 2007, 29; Allen & Hoekstra, 2015, 60). Guiding learners to structure an explanation of biological phenomena the levels of organisation still appear appropriate. We will elaborate on the challenges of this task in the next section.

7.3 What Makes Biological Explanations Complex? – The Students' Perspective

7.3.1 *Students' Difficulties for Explaining Phenomena*

Scientific reasoning is a day-to-day task for experts, but students have various difficulties explaining biological phenomena. As we argued in the previous section, the levels of organization contribute to the complexity of biology. Unsurprisingly,

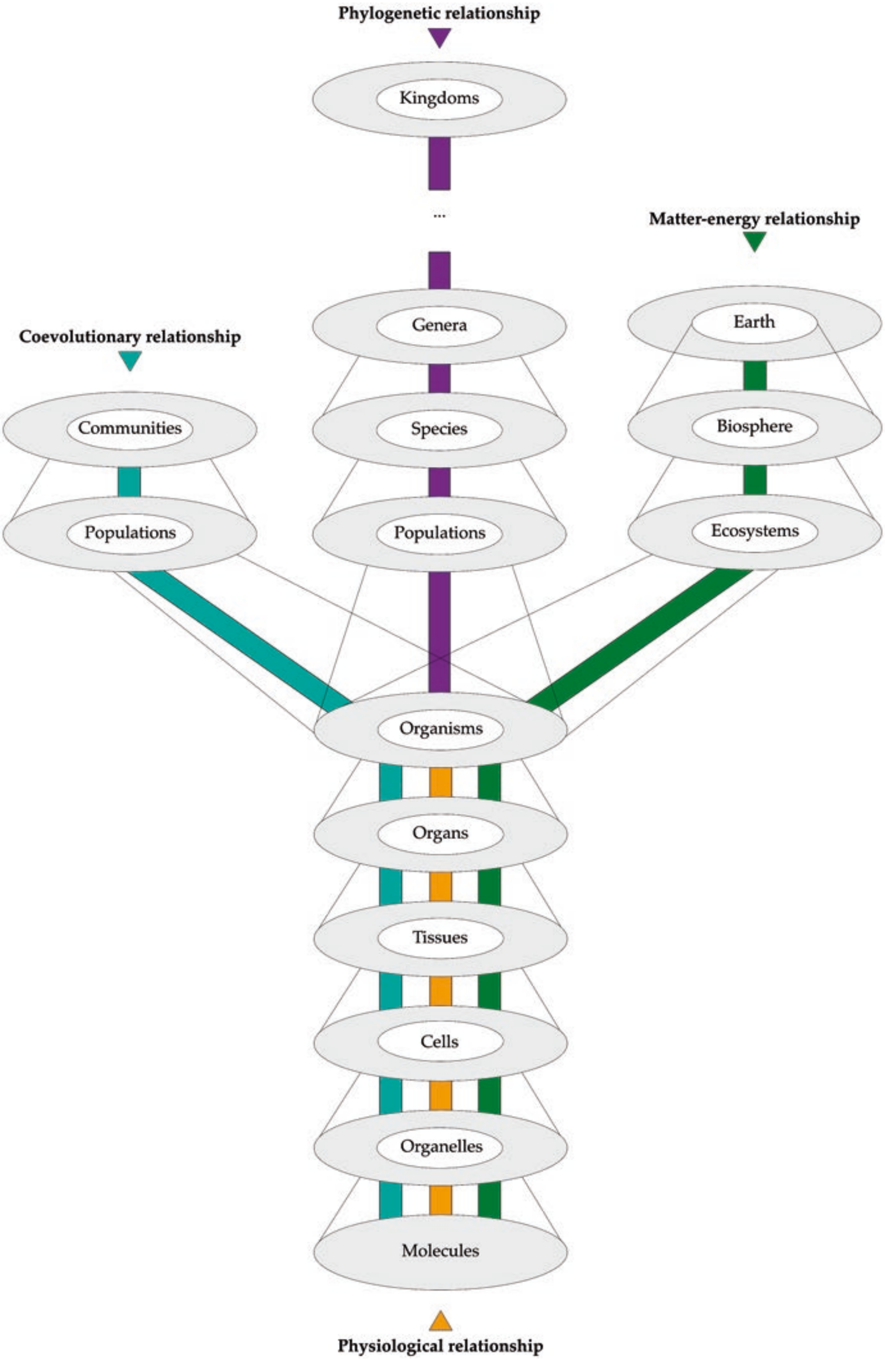

Fig. 7.2 A system of levels of organization for biology education. The system makes the relationships between the levels explicit and incorporates the idea of zooming. (Schneeweiß & Gropengießer, 2019, p. 14)

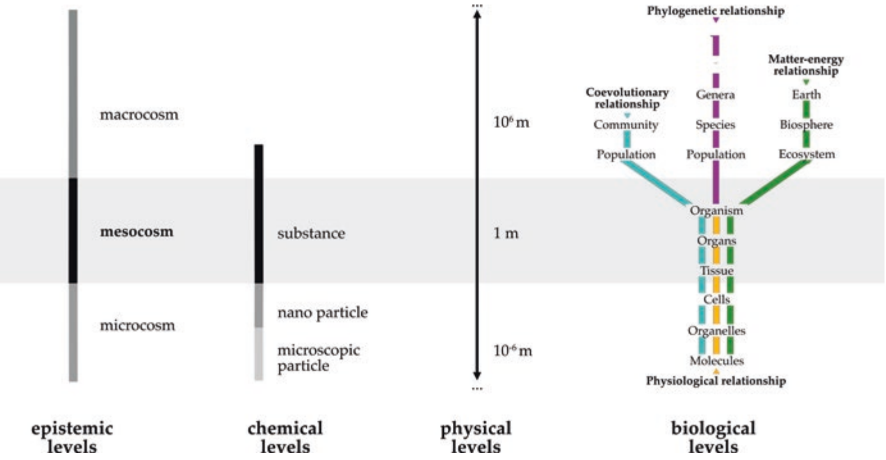

Fig. 7.3 Comparison of organizational levels of different scientific disciplines

minding the levels of biological organization seems to be a significant obstacle for students (Hammann, 2019). Research on many different biological topics, such as cell biology, genetics, or physiology, revealed learning difficulties related to levels of organization (Hammann, 2020; Schneeweiß & Gropengießer, 2019).

Typical difficulties are the confusion of levels (Wilensky & Resnick, 1999), explaining only on one level (Jördens et al., 2016), or failing to interrelate levels (Brown & Schwartz, 2009). For example, in ecology, some students can describe the processes of photosynthesis and respiration at the molecular level yet fail to interrelate the two processes at the level of the ecosystem (Brown & Schwartz, 2009). In this example, the individual elements of knowledge are not connected. This may be termed as fragmented knowledge. Learners may combine their fragmented knowledge differently, depending on the phenomenon, thus resulting in different explanations. (Clark, 2006; DiSessa et al., 2004; Izsak, 2005; Wagner, 2006). Learners often do not succeed in finding adequate causal explanations across the levels of organization. Therefore, interventions that foster the integration of knowledge are needed.

The difficulties described in the literature may be related to the construction process of an explanation, as we will elucidate in the next section.

7.3.2 *Zooming in on the Construction of Explanations*

Explanations are generated ad hoc. Students thereby interact (i) with the phenomenon, (ii) with incitement from peers, teachers, or texts, and (iii) with their own available cognitive resources, namely their conceptions, knowledge, and ideas. This "emergent construction in interaction" (Boersma & Geraedts, 2009; Schwarz et al., 2008) may lead to different explanations for similar phenomena. Guidance will help activate and integrate the available knowledge and draw useful connections between conceptions at different levels. Guidance should focus on the problem-solving process rather than the possible answers (Schwarz et al., 2008).

A fruitful structure for guiding the process of problem-solving and explaining in biology is the yo-yo learning and teaching strategy. Named after a famous toy, this strategy proposes moving up and down the levels of organization like a yo-yo (Knippels, 2002; Knippels et al., 2005). Our study relies on adapted yo-yo learning principles as listed in Table 7.1 (Jördens et al., 2016, p. 961; Tripto et al., 2016, p. 568).

We have now explored the complexities of biology from both the scientists' and the students' perspectives. In the following section, we take the educators' perspective and introduce learning principles and the zoom map.

Table 7.1 The zoom map supports yo-yo learning

Yo-yo learning (Jördens et al., 2016, p. 961; Tripto et al., 2016, p. 568)	Support by the zoom map
1. Distinguishing different levels of organization	The zoom map explicitly displays the system levels as stacked wide ellipses.
2. Identifying the entities and processes of a system (and relating them to a level)	System entities can be assigned to a system level by writing them into the ellipses. In Fig. 7.11, the cell membrane and the cell wall are assigned to the cell level.
3. Linking concepts at the same level of organization (horizontal coherence)	The system entities are linked by words or phrases forming propositions if the reading direction indicated by arrows is followed. The rules for the construction of concept maps apply. Propositions should be meaningful.
4. Linking concepts at different levels of organization (vertical coherence)	In the zoom map, one can zoom into each structure and describe the system at a lower level ($n - 1$). The different levels can be related vertically. See 11 as an example.
5. Thinking back and forth between levels (also called yo-yo learning)	In an effort to explain a phenomenon, learners should start at that very level. With the help of supporting material, learners can move downwards and explore each level repeating steps 1 to 4. Finally, based on their zoom map, they can try to give a mechanistic explanation of the phenomenon or identify missing knowledge. This step usually involves moving upwards in the zoom map.
6. Meta-reflection about the question of which levels have been transected	Moving across levels and reflecting on levels are an immanent process of the construction of a zoom map. The first reflection on levels occurs when system entities are assigned to levels. The second reflection on levels concerns the horizontal and vertical interrelations. In the construction process, learners have to discuss these interrelations. After the construction of an individual zoom map, meaningful comparisons to other zoom maps may support learning. The teacher should give feedback and orientation if needed.

7.4 Guiding the Process of Explaining with the Zoom Map—The Educators' Perspective

7.4.1 Theoretical Learning Principles for Teaching Complex Phenomena

The development of the zoom map is grounded on six key insights:

1. Biological phenomena need to be examined and explained at multiple levels. Depending on the phenomenon, explanations require different sets of levels, which relate to the various relationships that facilitate the levels. Explanations may use components from lower or higher levels of organization of a given phenomenon (Brooks, 2021; Novikoff, 1945; Schneeweiß & Gropengießer, 2019);
2. Levels of organization can bring structure to otherwise unstructured scientific problems if they are made explicit (Brooks, 2019; Hammann, 2019; Schneeweiß & Gropengießer, 2019);
3. To support students in explaining phenomena, teachers should structure learning environments according to systems thinking principles—for example, via yo-yo learning (see Table 7.1; Knippels, 2002). Teaching should focus on interrelating concepts within and across levels of organization (Hammann, 2020);
4. Students need guidance during the problem-solving process (Schwarz et al., 2008);
5. Students do not automatically consider the levels of organization; they need to be encouraged, and levels of organization have to be made explicit (Hammann, 2019; Reinagel & Bray Speth, 2016).
6. Zoom levels and zooming in and out are student-oriented metaphors for the levels of organization and change between them (Schneeweiß & Gropengießer, 2019).

7.4.2 The Zoom Map

To make the theoretical learning principles operative, we invented a tool to cope with the complexity of explaining biological phenomena—the zoom map. This new graphic organizer guides learners in the process of explaining and prompts them to consider the relevant entities and their relationships, as it makes levels of organization explicit. As the name reveals, the zoom map draws on the metaphor of zooming. This metaphor's experiential source domain is bringing an object near to the eye to see more details or stepping back to get an overview, not to mention image scaling on digital devices that allow magnifying or shrinking. Zooming biological phenomena consequently leads to stopovers at the levels of organization. Zooming in focuses on smaller sections of the scientific problem; zooming out takes the whole or the context into account (Brooks, 2019; Schneeweiß & Gropengießer, 2019). Moreover, zooming calls for relating the entities at the different levels. The zoom map fosters students' causal explanations across levels of organization through the inherent demand to consider the respective levels. Therefore, the zoom map may help students structure and interrelate fragmented knowledge and achieve integrated knowledge.

Within the levels, the horizontal relations were drawn similar to the mode of concept maps (Novak & Cañas, 2006). We adapted the concept map because it has already proven fruitful in the context of systems thinking (Brandstädter et al., 2012; Dauer et al., 2013; Schwartz & Brown, 2013; Schwendimann & Linn, 2016) and is known for its capability to foster conceptual interrelations (Fischer et al., 2002; Novak & Gowin, 1984; Van Drie et al., 2005). Combining zooming with concept-mapping is the core idea of the zoom map.

By zooming into an entity at one level, one reaches a lower level. In the zoom map, this is implemented in the following way: Ellipse shapes indicate levels of organization. Each level features its own concept-map displaying the structures and relations concerning a phenomenon. By zooming into the term that denotes a structure at one level, one reaches another lower level. Vertical arrows indicate vertical interrelation; horizontal arrows indicate horizontal interrelation (Fig. 7.4).

Since levels are phenomenon-specific, the zoom map layout may and should be adapted to the phenomenon in question. For example, explanations of physiological phenomena will require the level of the organism to give context and significance, the level in question, and the one below that gives the explanans, such as causes and mechanisms. In general, not less than three levels and their interrelations have to be considered for an adequate explanation of a phenomenon: the focal level, a level below, and one above (Allen & Hoekstra, 2015, 18). Depending on the phenomenon—for example, when comparing two different organisms—it may be adequate to juxtapose or diverge the zoom maps (Fig. 7.5).

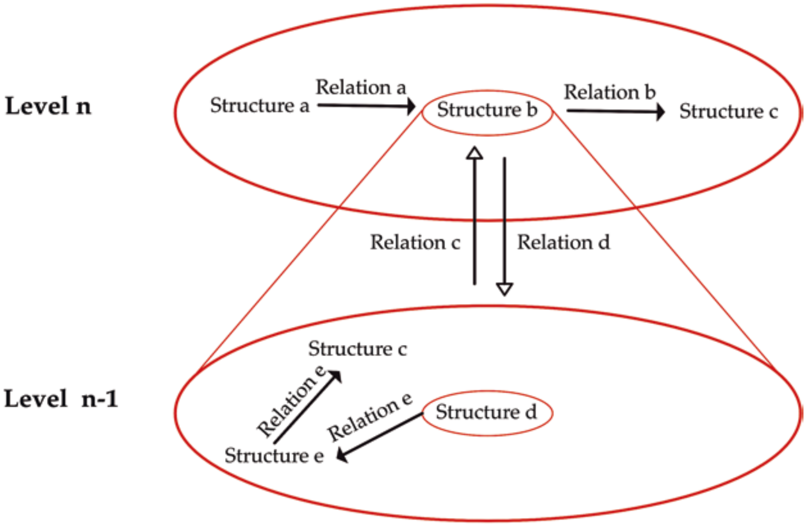

Fig. 7.4 Principle of the zoom map

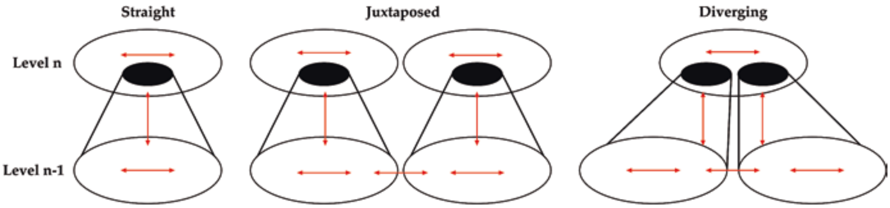

Fig. 7.5 Different ways of zooming in the zoom map. Red arrows indicate horizontal and vertical interrelation

To support students explaining phenomena, teachers should structure learning environments according to the principles of systems thinking—for example, with yo-yo learning (Knippels, 2002). The zoom map supports the construction of explanations according to systems thinking, as shown in Table 7.1. While yo-yo learning focuses on units or lessons, the zoom map focuses on the individual learning opportunity.

7.5 Design of the Study and Materials

In our study, we examined how students construct scientific explanations of the wilted painted nettle with the zoom map's help. We developed and conducted teaching experiments (Komorek & Duit, 2004; Steffe & Thompson, 2000), as well as a study design that is open and flexible and allows for interventions (see Fig. 7.6).

We showed two painted nettles (Fig. 7.7) and asked, "Why are the leaves of the left plant upright and the leaves one the right wilted?"; a typical student explanation would be, "Because the water went out" (Torkar et al., 2018, p. 2273).

The student's explanation is viable in everyday life, but a biologist would formulate a mechanistic explanation that connects water to the leaves' appearance and structure. A short version of a mechanistic explanation would be: Water filling the cells protoplast will be pressurized by straining the cell wall. The cell wall is a somewhat elastic, tensile strength structure. Due to its properties, the cell wall limits the expansion of the protoplast (Campbell et al., 2008, p. 770; Thoday, 1918). The hydraulic interaction between protoplast and cell wall results in a turgid cell, comparable to an inflated football. Interacting with the other cells of the mesophyll, the leaves become turgid, comparable to several inflatable tubes that form a boat. This mechanistic explanation spans several organization levels, such as organelle, cell, tissue, and organ. We included these levels in our material, as we will demonstrate in the next section.

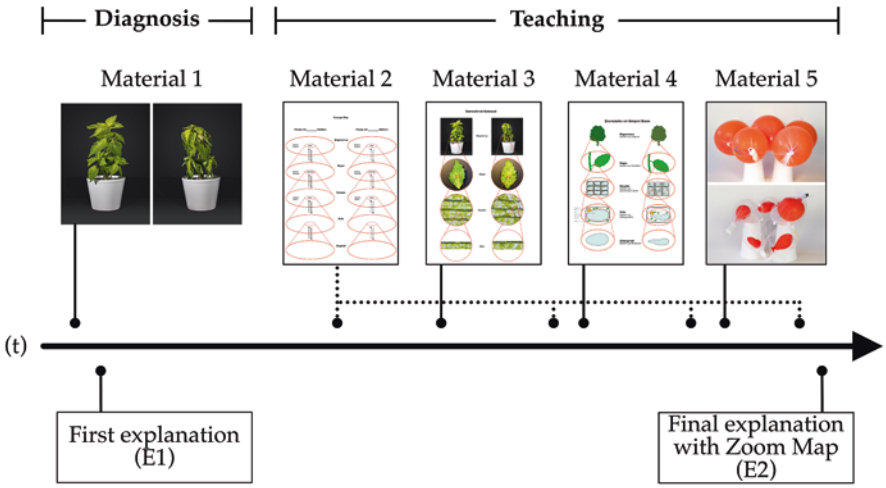

Fig. 7.6 Timeline of the teaching experiment

Fig. 7.7 Material 1 (M1) shows a painted nettle (Coleus scutellarioides) in regular and wilted condition

7.5.1 The Zoom Map Prepared for a Particular Explanation

The students received a series of instructional materials (M2–M5). Apart from the material, the teacher offered no further explanation of the phenomenon. Instead, the teacher instructed the students to interact with the material with impulses such as "describe" or "what do you see?". The first material that the students received was the zoom map (M2). Since students had never worked with this tool, we chose a semi-structured approach. The zoom map already displayed the relevant levels of organization (Fig. 7.8). Throughout the teaching segment, we asked participants to complete the zoom map.

7.5.2 Experience-Based Conceptions Are Needed to Construct an Explanation

The zoom map is intended to guide the process of a phenomenon's explanation. Even if the phenomenon is plainly perceptible, the causal explanation entities are probably not well known. Students need to develop conceptions based on experience with the phenomenon. This experience is especially relevant if students have to consider levels that are within the microcosm (Niebert & Gropengiesser, 2015). Therefore, one key aspect is that students get the opportunity to investigate the phenomenon themselves or are provided with external representations of entities and their properties. Ideally, the phenomenon at all relevant levels of organization is depicted (Figs. 7.9 and 7.10). We show our worksheets on the phenomenon of wilted and erected leaves as an example.

7.5.3 External Representations Depict the Mechanism

We handed the participants two models that were intended to represent the mechanism needed for explanation. The models consisted of balloons connected with nets. One model had firm and one limp balloons. The balloons were intended to represent the protoplast, the nets the connected cell walls at the level of tissue. At the end of the teaching experiment, students were asked to explain the phenomenon based on their zoom map (E2: final explanation with the zoom map).

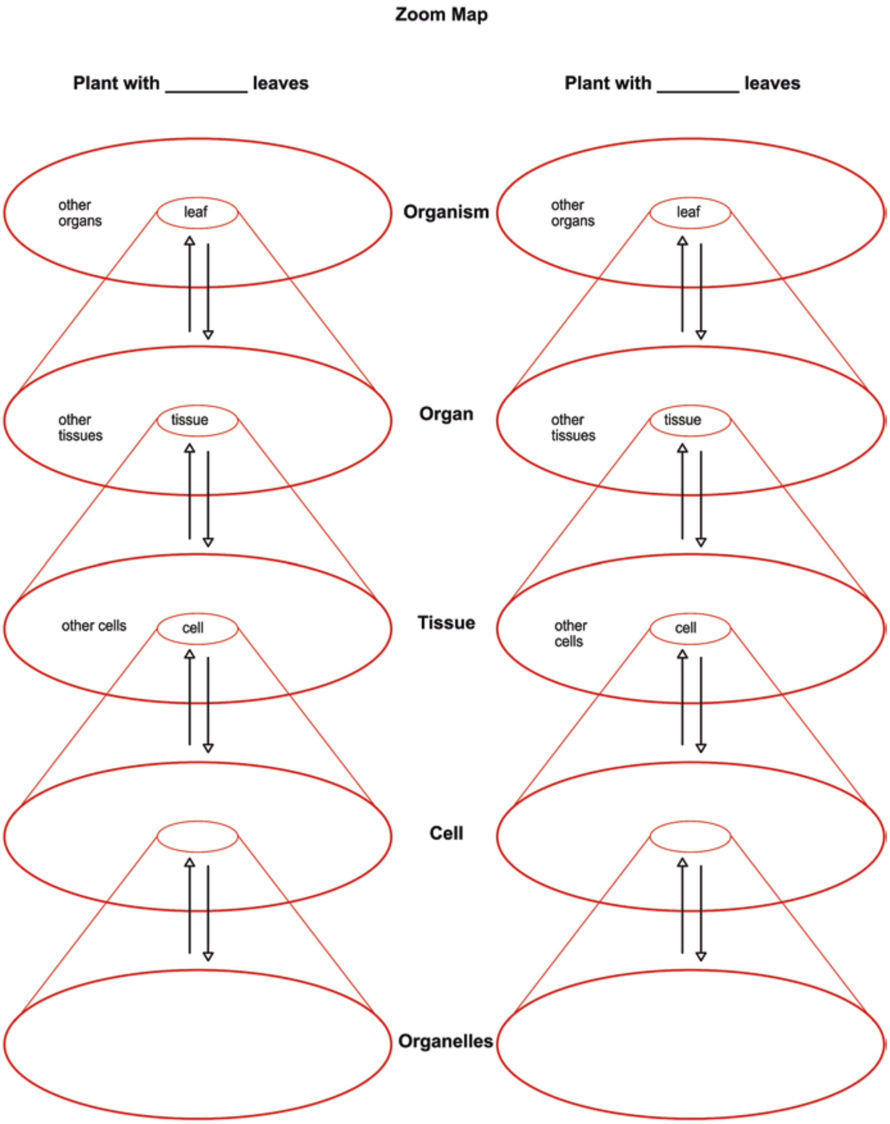

Fig. 7.8 Material 2, the zoom map used in the teaching experiment (translated)

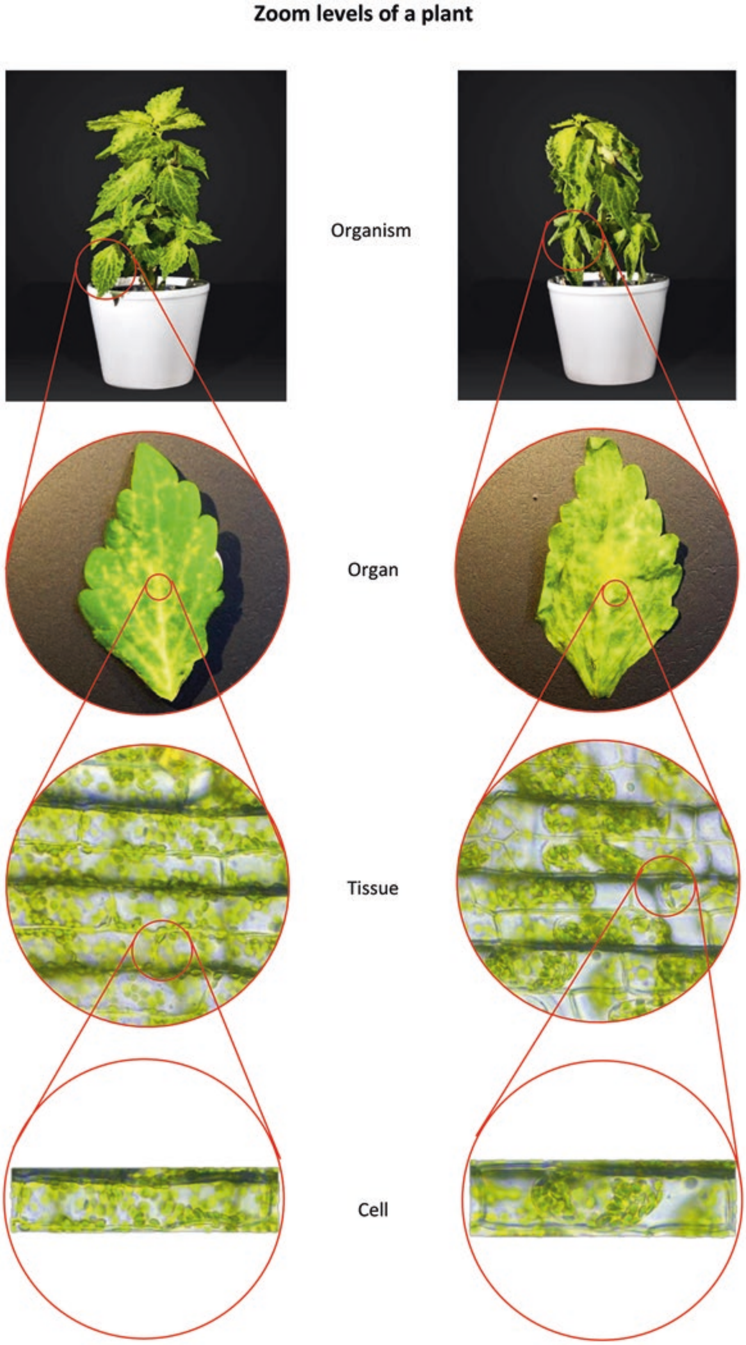

Fig. 7.9 M3 shows photographic images zooming from organism to cell

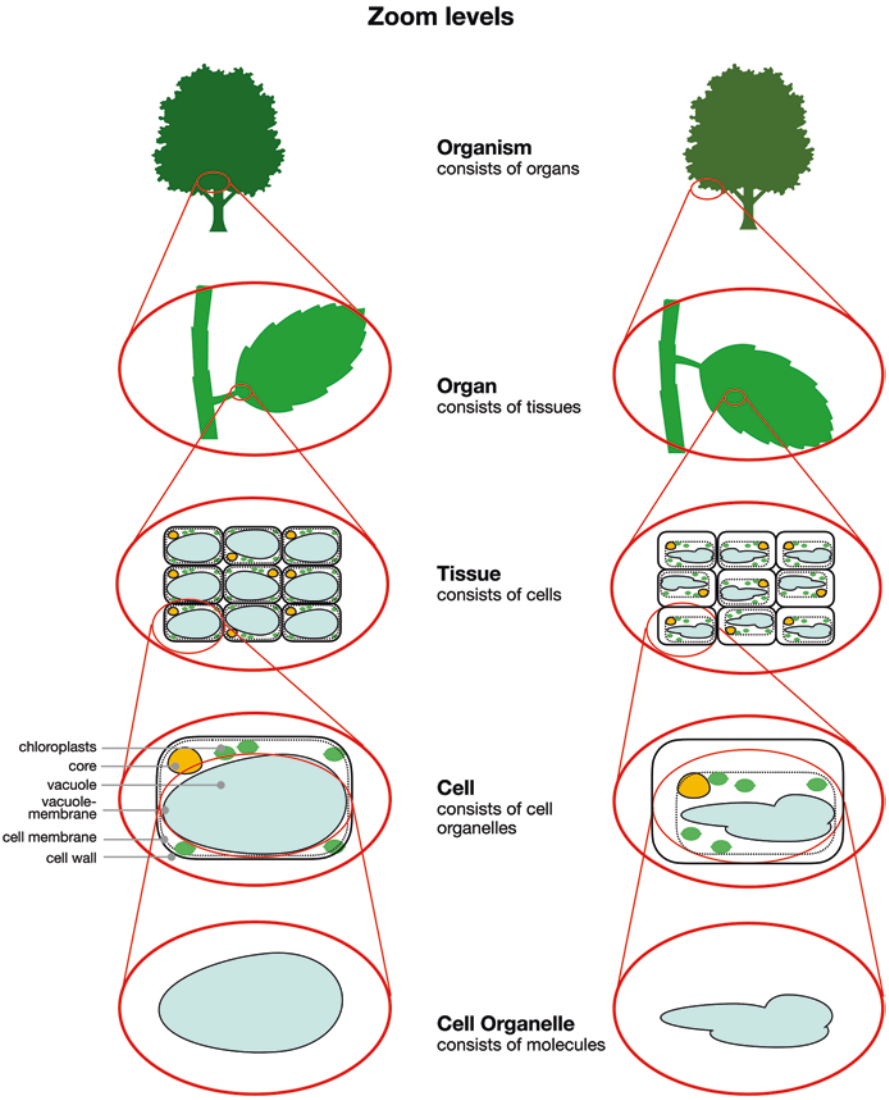

Fig. 7.10 M4 illustrates the phenomenon from the level of organism to organelle

7.5.4 Participants

We conducted the teaching experiment with 13 students in seven groups. The students attended a public high school in northern Germany. For analysis, we recorded the audio and video of each teaching experiment. On average, the teaching experiments lasted about 48 min (Table 7.2).

Table 7.2 Participants

teaching experiment	A	B		C		D		E		F		G	
Students	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
Age [years]	15	17	16	16	17	16	16	16	16	17	17	17	17
Duration [min]	43	50		78		39		40		49		38	

7.5.5 Analysis

To prepare the analysis, we transcribed the interviews. During the interview, the student edited the zoom map (Fig. 7.8) by filling in their explanation of the phenomenon on different levels of organisation. For further analysis, we scanned and digitized the student-edited zoom maps.

We then identified the sections of the interviews relevant to the explanation of the upright and wilted leaves. We named these sections the first explanation (E1) and final explanation with the zoom map (E2). The analysis was based on the computer-supported qualitative analysis (Kuckartz, 2010).

To investigate the levels of organisation and the direction of the students' explanations, we developed a code system. One part of the code system were the levels of organisation: organism, organ, tissue, cell and organelle. The other part of the code system concerns the direction of explanations. We expected five different directions: one level only with no direction in the proper sense, downwards, upwards, downwards-upwards, and upwards-downwards. All six transcripts were coded by the first author and discussed with the second author. If statements were unclear, we investigated the zoom maps of the respective students. If the statement was not related to a level on the student-edited zoom map, we categorised it as 'not defined'. We present the results of the analysis in the following section.

7.6 Results

To provide an example of the interaction with the zoom map and the resulting explanations, we describe teaching experiment C. In the remainder of this section, we illustrate the process of working with the zoom map and explain why exhaustive editing is needed. Finally, we analyze the students' explanations with regard to the levels of organization and the direction of the explanation.

7.6.1 A Zoom Map to Explain Upright and Wilted Leaves

The zoom map of teaching experiment C explains the phenomenon at the relevant levels (organism to organelle) and interrelates system parts. Downward links are labeled with "consist of" (Fig. 7.11). Students, therefore, used the part-whole

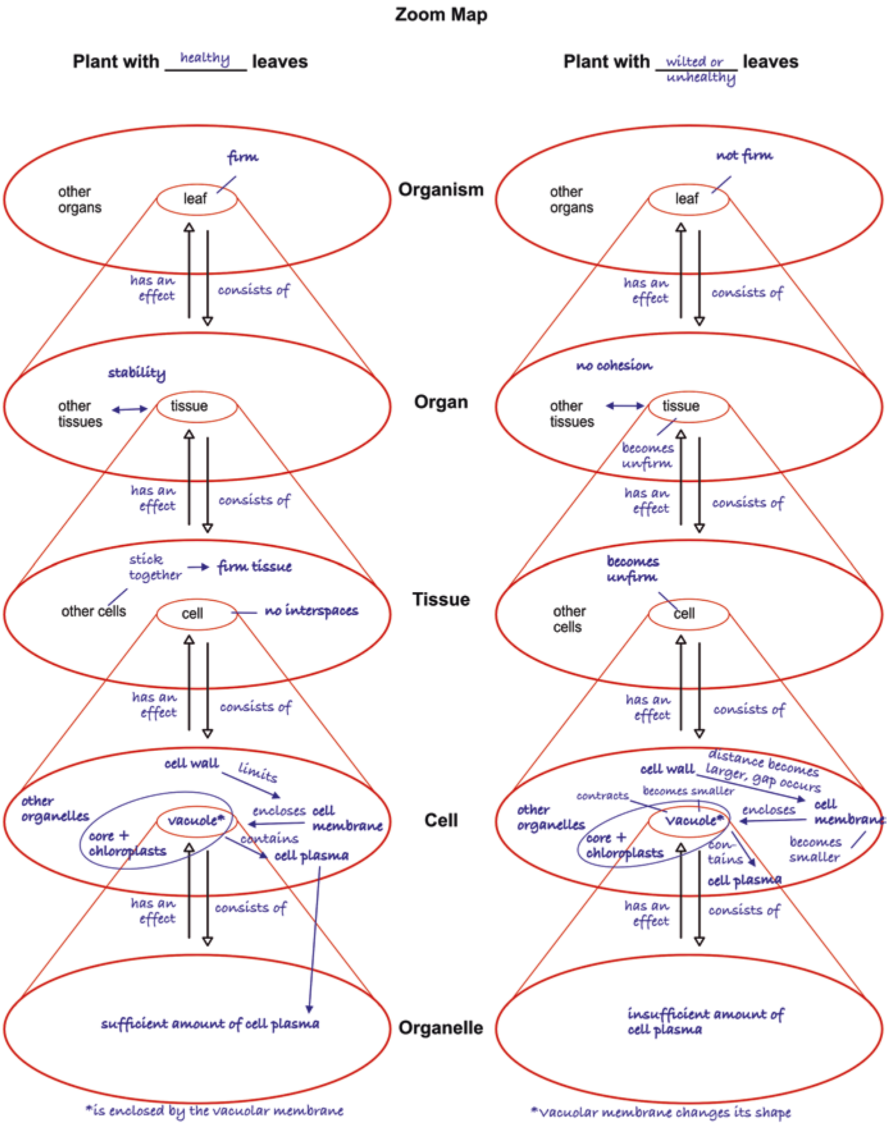

Fig. 7.11 Zoom map constructed by students S4 and S5 of teaching experiment C. The students' answers are shown as handwritten. (digitalized and translated from German)

scheme to explain how lower and higher levels were related. The lower levels have "an effect" on the higher levels, as labeled on upwards links.

Based on their zoom map, Student S4 and S5 explained the phenomenon as such (translated from German):

S5: "Well, the individual cells are filled in a fitting manner by the nucleus, chloroplasts, and also the vacuoles, which actually take up a large part of the cell. Therefore, when the vacuole is filled with sufficient quantity, it presses against the cell membrane, and this, in turn, presses against the cell wall, which is why the individual cells are very stable—because they are pressed from the inside out and cannot collapse somehow. Therefore the cells are—no, therefore the tissue, which consists of different cells is also … well, it presses everything against each other, and that is why it is very stable, and then individual tissues press against each other, and that is why the whole leaf is filled from the inside and cannot collapse at all—because everything is filled from the inside." (C, S5, l. 317)

S4: "Then with wilted leaves … so the general problem is that there is too little cell plasma, and this is the reason why the vacuole decreases. Because there is too little water or too little substance in it, it [the vacuole] contracts and because it takes up a large part of the cell, the cell membrane, and in general the whole cell, is shrinking. Therefore, it can no longer fill the cell as a whole, meaning on the outside. And that's why gaps are created that then make the whole unstable. If we are now here at the tissue level and there is no cohesion within the cell membrane and the outer part [cell wall], it limits it, doesn't it? Well, in any case, it [the tissue] becomes unstable because of these spaces that are created by this, and the whole leaf appears to be withered." (C, S4, l. 318)

In their explanation, students S5 and S4 addressed the levels from organ to organelle. To explain the upright leaf, student S5 started at the cell level by describing its filling. He then switched to the level of the organelle and reported that the vacuole was filled. His explanation of the interaction between vacuole, cell membrane, and cell wall (pneu principle) was at the cell level. He continued with the tissue level in his explanation: stable cells pressed against each other, which made the tissue stable. At the level of the organ, tissues pressed against each other, making the leaf itself stable.

Student S4 explained the withered state. Its mechanism started at the organelle level, with missing cell plasma in the vacuole followed by contraction of the vacuole. The student then switched to the cell level and reported that the cell was shrinking and that gaps were created that had an effect on the level tissue, which became unstable. Therefore, the leaves appear withered.

7.6.2 A Zoom Map Demands Exhaustive Editing

The difficulties that students face during the construction of a zoom map can be turned into learning opportunities. As an example of a zoom map that can be improved, we present the map of teaching experiment G (Fig. 7.12). The zoom map explains the phenomenon only at the levels of tissue to organelle. Most of the few interrelations that were drawn are unlabeled. In their final explanation, the students did not further elaborate on these unlabeled arrows.

With their zoom map, the students offered the following final explanations of the phenomenon:

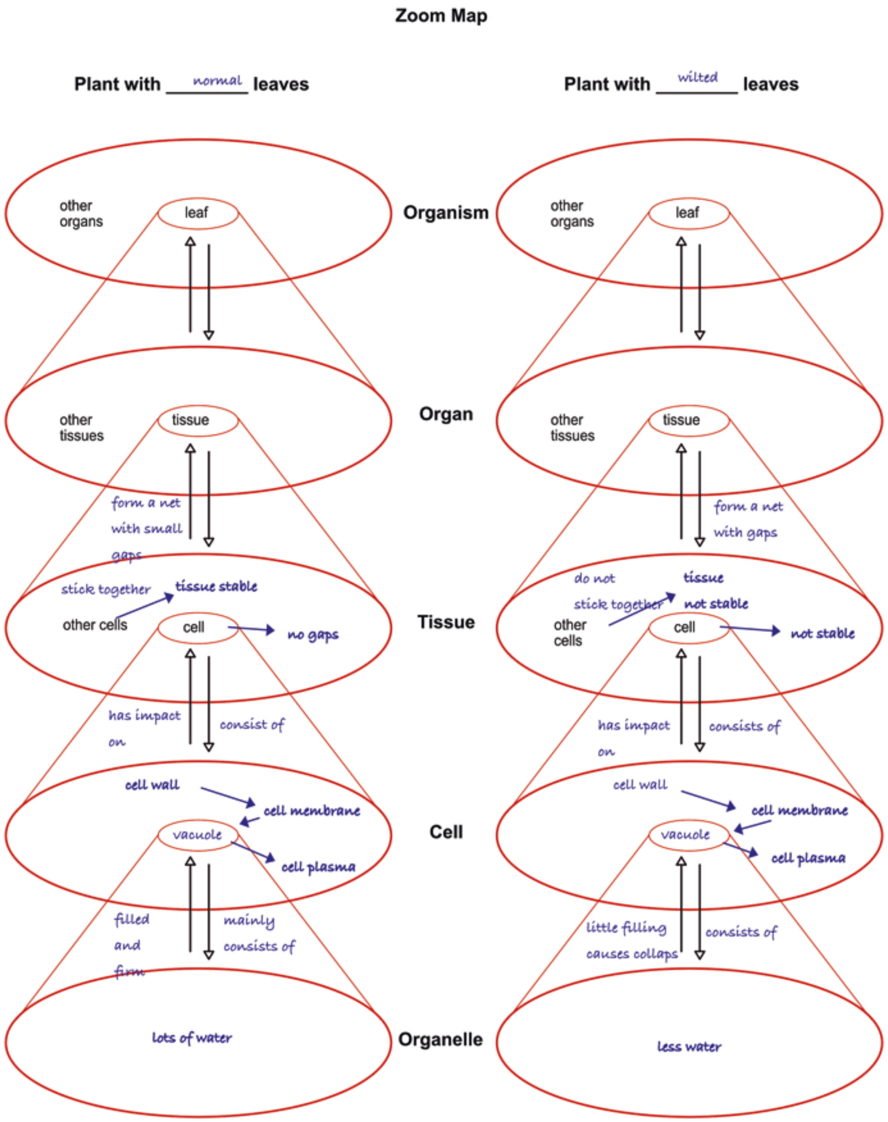

Fig. 7.12 Zoom map constructed by students S12 and S13 of teaching experiment G. The students' answers are shown as handwritten. (digitalized and translated from German)

S13: "Yes, I would say the phenomenon simply refers to the vacuole. That is, it [the vacuole] has the greatest effect on the appearance of the plant. Simply, if there is a corresponding amount of water or cell sap, whatever, that fills the vacuole. Then the leaves will look green, and they will stand by themselves. And the less water is in this vacuole, the more wrinkled and wilted these leaves will look. And then they don't have as much stability."

(G, S13, l. 224–229)

S12: “Yes, well, I think it is also possible that the plant is drying up or simply was not watered … that is, then it dried up. And because of that, there is too little water or cell plasma in this vacuole, as you just said. This causes the cell, no, the vacuole, to contract. Thus, it also shrinks the cell. The cells are no longer in good contact with each other. This causes gaps to form, and the tissue … so this is the tissue. And on the organ level, it just withers and collapses.”

(G, S12, l. 230–336)

In their final explanation, students S12 addressed levels from organism to organelle, while S13 skipped the levels of tissue and cell. S13 did not describe a mechanism but presented the vacuole (level of organelle) as the cause of the leaf’s appearance. This may be due to the unclear interrelations at the level of the cell and the tissue. The explanation of S13 was closer to a mechanism. At the level of organelle, he pointed to missing water and filling of the vacuole. He mentioned the vacuole’s contraction and the cell at the level of the cell, although he did not write it down in his zoom map. With cells not being in contact with each other, the tissue was a “net with gaps.” The leaf was therefore withered.

A zoom map requires exhaustive editing. Students may tend to write down only parts of their explanation at first. In that case, they need to be motivated to complete their explanation and thus visualize it exhaustively. In our teaching experiment, we asked all students to develop their zoom map further and label the interrelations. In a classroom setting, the students would present their zoom map to be discussed by their peers.

By asking, “How does the vacuole affect the leaf?”, we made the missing interrelations explicit. Since S13 skipped the levels of tissue and cell, he might not have been able to label the interrelations at these levels. In cases such as this, students should write down questions and difficulties arising during the construction process.

7.6.3 Learners Drill Down to Lower Levels in Their Explanations

Addressing the required levels of organization is a guideline for teaching complex phenomena (see the first section). We therefore expect students to address (more of) the relevant levels.

The first explanation was conducted without the zoom map. Twelve students put forward an explanation; one student (S10) did not explain the phenomenon. An example of a first explanation mentioning only the two levels organism and organ is:

S1: “On the right [plant], the [leaves] are partly curled up as if they were contracting, as if there was some kind of lack of liquid. So, the leaves also contain liquid somehow and as if that would be missing. The left [plant] is different; it looks healthy, like normal leaves. […] This is because the plant on the left has been watered and treated sensibly.” (A, S1, l. 7-11, translated)

In the first explanation, students focused on the level of organism (eight students) and organ (eight students). One student each considered the levels of tissue and cell. None of the students addressed the level of the organelle.

In the final explanation of the phenomenon, 12 students put forward explanations; student S7 did not explicitly explain the phenomenon. After instruction, student S1 explained the phenomenon at levels from the organelle to the organism:

"S1: "This is because in the cell organelles, the vacuole, they contain liquids. And in the healthy plant, there is simply more liquid in the vacuole than in the dried-up one; there is less. Because of this, the cell membrane contracts because of the less [liquid], and there is space between the cell membrane and the cell wall. The cell membrane encloses the nucleus, the chloroplasts, and the vacuoles. Here, the nucleus and the chloroplasts are present in both [plants], but the difference lies in the size of the vacuoles. And this is where it contracts.

I: What contracts?

S1: In the dried [plant]. […] The cell membrane contracts, and the cell wall remains the same. This means that there is some space in the tissue between the two, and that is why it seems to have shrunk. And here, in the healthy [plant], the cell membrane needs more space to enclose the larger fluid in the vacuole. […] This means that there is less space in between, and the leaf looks healthier because there is more liquid in it." (A, S1, l. 166-170, translated)

Students addressed the relevant levels for the causal argument in the final explanations guided by the zoom map. Eleven students elaborated on the organ and organelle levels, and 10 students on the level of tissue. Eight students each addressed the levels of organism and cell. Overall, in the final explanation with the zoom map, students considered more and lower levels. In some oral explanations, students addressed different levels than in their zoom maps, as shown for teaching experiment G (Fig. 7.13).

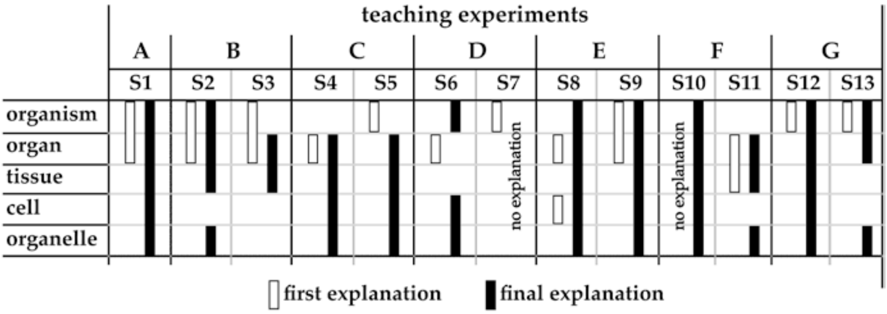

Fig. 7.13 Levels that students addressed in their oral explanations

7.6.4 Direction of Explanation: Top-Down, Bottom-Up, or yo-yo

One guideline of yo-yo learning is moving up and down (or down and up) the levels of organization. Since the zoom map should support yo-yo learning, students should be enabled to move across them.

We identified five possible directions of explanation: one level only (O) with no direction in the proper sense, downwards (D), upwards (U), downwards-upwards (D-U), and upwards-downwards (U-D).

Of the first explanations, we coded seven explanations as O, focusing only on one level of organization. An example of an explanation at one level only is the first explanation of S7: “Maybe the plant has not been watered” (D, S7, l. 4). Three explanations could be rated D; they moved from a higher level of organization to at least one lower level. Two students gave an explanation that we rated as D-U. Their explanation moved to a lower level and back to higher levels. None of the first explanations moved upwards or upwards-downwards—arguably, because the microcosm entities such as cells or organelles are not as familiar as mesocosmic leaves or plants.

The direction of most students’ explanation changed in the final explanation: seven moved U, four moved D-U, and one moved U-D. None of the final explanation was rated O or D.

In general, the direction of students’ explanations shifted from O or D to U or D-U (Table 7.3). The yo-yo principle, that is, D-U or U-D, was realized two times in the first explanation and five times in the final explanation.

7.7 Discussion

Our results indicate that the zoom map fosters explanations across the levels of organization.

In our analysis of the students’ first and final explanation, we were able to point out two aspects: First, after learning with the zoom map, students considered more of the relevant levels. Second, the students considered lower levels—those of the cell and the organelle (Fig. 7.13).

In our analysis of the direction of explanation, we were able to show that the direction of their explanations changed (Table 7.3). While the prevalent first explanation was restricted to one level only, the prevalent direction in the final explanation was upwards, and five out of 12 students even used the yo-yo principle to some extent.

To explain the case of upright and wilted leaves in everyday situations, one may refer to the mesocosm, namely sufficient or missing water. This explanation is sufficient in everyday life, because it leads to the appropriate action of watering the plant.

Table 7.3 Direction of students' explanation (O: One level only, D: Downwards, U: Upwards, D-U: Downwards-Upwards, U-D: Upwards-Downwards)

	First Explanation (E1)					**Final Explanation (E2)**				
	O	**D**	**U**	**D-U**	**U-D**	**O**	**D**	**U**	**D-U**	**U-D**
S1				●				●		
S2	●									●
S3	●								●	
S4	●							●		
S5	●							●		
S6		●							●	
S7	●					no explanation				
S8				●					●	
S9		●							●	
S10	no explanation							●		
S11		●						●		
S12	●							●		
S13	●							●		

Most of the students in our teaching experiments initially brought forward a similar explanation of the organism and organ levels. Only a few explanations went beyond entities that can be seen with the naked eye. A biological explanation, in contrast, is more challenging because it includes a mechanism. The phenomenon that should be explained, in most cases, needs to be related to lower levels of organization that lie within the microcosm—a part of reality that is only accessible through the use of science-based technologies such as microscopes. Processes in the microcosm are predictably hard to understand (Niebert & Gropengießer, 2015).

Students, therefore, need support through visualizations or models (see M3-5, Figs. 7.9 and 7.10).

Since biological phenomena are context dependent, inquiries should not only consider downward questions, but upward questions as well (Allen & Hoekstra, 2015). This is in accordance with yo-yo learning (Knippels, 2002) and can be supported by the zoom map.

In our teaching experiments, students managed to construct zoom maps that explained the upright and wilted leaves of the painted nettle, albeit the maps differed in the explanation's quality. Working with a zoom map will not by itself lead to a correct explanation. To grasp the scientific explanandum's mechanism, learners need to understand and apply the pneu principle as realized in footballs or plant cells and extend it to the level of tissue, leaf, and plant. A pneu consists of a flexible but tensile hull and a pressurised filling (Frei, 1994).

However, the zoom map can explain the relevant levels by demanding explicitly stated relationships between the entities at different levels and asking for links within and between levels. Even if not all aspects of an explanation are known or understood, one can identify the knowledge gaps. Nonetheless, exhaustive editing is a prerequisite. Zoom maps can be easily compared, and discussions can be conducted in a highly structured manner.

7.8 Implications for Biology Teaching

Students have difficulties in constructing adequate explanations of complex biological phenomena, especially when they require them to move between different levels of organization. For adequate explanations, students need experience-based conceptions of a phenomenon. This experience may be achieved through models or experiments. However, conceptions alone are not sufficient, as appropriate integration is what primarily poses difficulties to students. Hence, learning environments and biology teaching should be structured according to systems thinking principles—for example, via yo-yo learning. Levels of organization should therefore be made explicit. Students do not consider them on their own accord; they need guidance and reason to do so. The zoom map can be used to guide students across levels of organization and foster adequate explanations. With the zoom map, students consider more and lower levels of organization and change between levels.

Yo-yo learning has already been used to teach complex phenomena such as genetics. As our results demonstrate, the zoom map can be a fruitful tool to implement yo-yo learning guidelines in the classroom. We anticipate that this tool can be used in other fields that require explanation at multiple levels, such as chemistry.

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