
EXPlainistry: Creating Documentation, Explanations, and Animated Visualizations of Chemistry Experiments Supported by Information and Communication Technology To Help School Students Understand Molecular-Level Interactions

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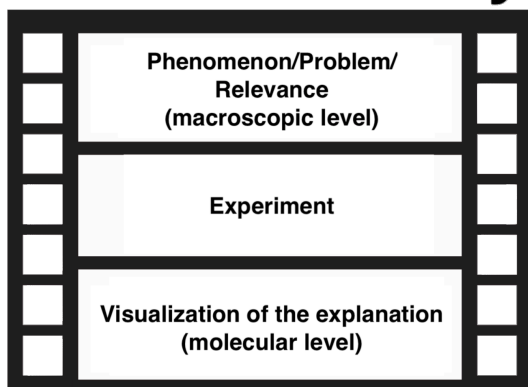
ABSTRACT

Given that students are constantly communicating and documenting special experiences in their social and private lives with digital devices, we suggest that this behavior could be used to record and deepen learning experiences – such as visualizing reactions at the molecular level – in a chemistry class. An example would be the creation of stop-motion videos to aid the visualization process for the documentation of experiments. This approach makes use of well-established techniques for documentation and visualization (e.g. static models or pictures) and combines them with dynamic approaches (e.g. animations) in order to enhance explanations of chemical experiments. Here, we describe how we use this approach to augment the novel teaching method, EXPlainistry (experiments explained in chemistry) with 5th to 12th graders, and consider how it helps students use ICT

(Information and communications technology) in order to document, explain and visualize experiments in chemistry education.

GRAPHICAL ABSTRACT

EXplainⁱstry



25 KEYWORDS

High School / Introductory Chemistry, Collaborative / Cooperative Learning, Computer-Based Learning, Inquiry-Based / Discovery Learning, Misconceptions / Discrepant Events, Multimedia-Based Learning

INTRODUCTION

In 2016, Jordan et al. found that students with the help of self-created videos have a higher
30 learning success and autonomy in experimenting and understanding than students without this
method.¹ Also, Benedict and Pence have already discussed in 2012 the possibilities of using self-
created videos in chemistry education.² However, it deals exclusively with the use of ICT (Information
and communications technology) for experimenting and documenting chemical reactions at the
macroscopic level. It is important to properly document an experiment on this level. A major problem
35 in chemistry lessons is the consideration of processes at the particle level. Jones described in 2013 the
importance of such a multimedia-based molecular visualization of the reactions discussed in class.³
Johnstone mentioned already in 1982, the importance of this cognitive separation.⁴ To demonstrate
the separation of those levels, water can be used as a prime example. The macroscopic level can be
seen in a drop of water, as it describes what the eyes can directly observe. The molecular or
40 microscopical level shows water on its particle level. The symbolic level is the third way to describe
water, with its formula H₂O. Those three levels need to be separated from each other and will also play

an important role in using EXPlainistry (“Experiments explained in chemistry”) in chemistry education.

Another important aspect in chemistry education is the relevance of chemical reactions in students' everyday life. In 2013, Stuckey et al. described how the relevance of students' learning changes over the course of their education.⁵ The idea of developing the EXPlainistry format, is to bring these three elementary aspects of chemistry teaching together and at the same time develop an additional diagnostic tool for the instructors. By using the method EXPlainistry the instructor is able to receive a visual interpretation of the student's imagination by combining relevance, experiment and particle level imagination. After a successful diagnosis, this can lead to an individualized help for each student.

Computers, as typical representatives of ICT, enrich learning by unlocking methodological diversity⁶. An example of visualization and explanation within the teaching of chemistry is EXPlainistry developed by our team. The basic didactic method underlying this approach is called “learning by explaining”, where the students create short – three to five minutes – explanatory videos.⁷ Chemistry education puts the main emphasis on experiments and is therefore more tangible than other subjects, like languages or liberal arts. EXPlainistry is another approach that makes use of this tangibility and actively includes students within their classroom setting. Importantly, it is student-centered and incorporates several key guiding principles of learning, such as product and process orientation, and reflection on the learning process itself. When creating these videos, students should primarily experiment independently and also think about the explanation that they give to their classmates in order to capture the ideas conveyed by the accompanying images. Through the use of digital media and associated methods as learning tools, the students can be guided towards the required academic goals of a chemistry course. In an informal lesson, students can create such clips in small groups for either the same or different experiments or topics. The “Learning by Explaining” approach in the style of EXPlainistry cultivates each group to independently develop expertise and knowledge (in the field of experimental and specialist knowledge) and incorporate it in a self-invented storyline suitable for their classmates in an explanatory film. Similar to a “conventional” pen-and-paper experimental documentation, an EXPlainistry has a defined structure. ICT devices are merely a

70 tool to consolidate and deepen the content learned. This form of a digital learning product is suggested
to help students to learn or revise content while it also serves as an additional evaluation component
and above all as a diagnostic aid for teachers. Furthermore, it comes to a change of roles within the
classroom between teachers and students. In addition, it comes to a role change between teachers and
students. Besides keeping grading the learning outcome in focus, EXPlainistry is about students
75 becoming instructors for their own classmates. The following paragraphs describe the didactical
function of our method and demonstrate an example of how to include EXPlainistry in a chemistry
class.

80 **FUNCTIONS OF ICT IN CHEMICAL EDUCATION AND THE POWER OF INDIVIDUALIZATION**

By way of designing individual learning support, ICT can have different operating modes, at the
center of which are three main functions^{8,9}:

- As **learning tools**, ICT can methodically enrich the learning variety in chemistry
lessons. This can range from simple information acquisition to the use of animations up
85 to the creation of self-explanatory formats, such as EXPlainistry.
- As **experimental tools**, ICT help with experimentation in science education. This can
range from simple data logging sensors to integrated high-speed or even thermal
imaging cameras.
- As **learning companions**, ICT enrich learning beyond the formal classroom setting.
90 They are always present, covering multiple subjects, not just chemistry and cross over
into leisure time. This is especially important when combining formal, informal and
non-formal learning.¹⁰

If ICT is used for the method EXPlainistry, it can be classified as a Learning Tool used in the
95 didactic model “Learning by explaining”. The main focus of EXPlainistry is a descriptive video and
simulation at the molecular level. The students are the authors and producers of EXPlainistry, which
can be evaluated by the teacher as well as other students. In science education, it is recommended

that explanation videos are used to describe the basis of visible –macroscopic– phenomena due to molecular –microscopic– properties. An example could be for an introduction to the properties of organic compounds.¹¹ In this context, it is important that visualization of phenomena at the
100 microscopic level should stay at the molecular level and should not be mixed with the other corners of Johnstone’s triangle. Furthermore, the relevance of the problem plays an important role in EXPlainistry. For this reason, we consider Mahaffy's theory to extend the Johnstone triangle by another corner to a tetrahedron¹². This corner represents the human element. During the entire
105 working phase of EXPlainistry, students should be aware of where they can find such phenomena in their environment. Exactly this aspect describes Mahaffy’s additional human element.

An additional benefit is the possibility to animate or simulate the molecular level which is almost impossible to do on a static board in front of a class.¹³ For example, animations have positive effects
110 on building up chemical basic concepts such as the donor-acceptor-concept.¹⁴ For this reason, these types of visualization should be included in the process of learning in chemistry education. Self-created stop-motion clips are an easy way to implement these forms. Such videos can bring molecular events to life and convert static pictures into dynamic animations by taking single pictures and cutting them together as a short video. Thus, EXPlainistry combines the capability of a tablet to be used to
115 document an experiment, with the visualization of the molecular level as described above. In the following paragraph, we will show how to create an EXPlainistry. Furthermore, we will describe the added value this method provides for chemistry education.

EXPLAINISTRY – EXPERIMENTS EXPLAINED IN CHEMISTRY

The thought process and design of EXPlainistry requires a new form of documentation of
120 experiments in chemistry education. It is structured in three parts: Firstly, the students shortly explain the relevance of the experiment and/or the underlying problem. Secondly, they document the experiment and thirdly, they add an explanation on molecular level. In order to successfully achieve this, it is recommended that the students write a short storyboard about their EXPlainistry in order to structure their knowledge of the subject beforehand. An storyboard template is available to download
125 as supportive information.

Construction

The relevance

The relevance of a topic/phenomenon/problem for a student has an immense influence on their process of learning and understanding.¹⁵ It is important that each student discovers the dimensions of science education in daily life independently. This can be shown in a short (10 – 20
130 seconds) video clip that is presented at the beginning.

The experiment

This part of EXPlainistry includes the documentation of an experiment. In addition, it can include more than a standard pen and paper documentation. At first, the construction and
135 performance of the experiment is documented not only with words but also with a short graphical depiction to bring the practical aspects of an experiment into focus. This could be with the help of pictures, supported by voice recordings by the students.

The recording of the full experiment has two different advantages. The real-time recording with the camera app correlates with the way students document their experiences in everyday life. Another
140 advantage of using the camera app is that the recorded video can be used for repetition, zooming, slow-motion, or accelerating parts of the documentation. This can help to reflect the experiences later in the lesson or while learning at home. Different camera applications can also help with the visualization of hidden parts of an experiment. Fast running experiments, like an exploding balloon filled with hydrogen, can be easily shown in a slow-motion video, whereas slower reactions, like the
145 corrosion of a sacrificial anode, can be recorded by time-lapse photography.¹⁶

The explanation on molecular level

Bringing processes to life at the molecular level is the biggest added value of EXPlainistry, and ICT can help open new dimensions of animation and visualization.¹⁷ For example, chemical reactions
150 always include dynamic processes, which may include electrons/proton transfer reactions or the visualization of an equilibrium system. All of these are part of a chemical reaction that is difficult to visualize on a standard board in class. Students can easily create these animations in a video sequence on their own.

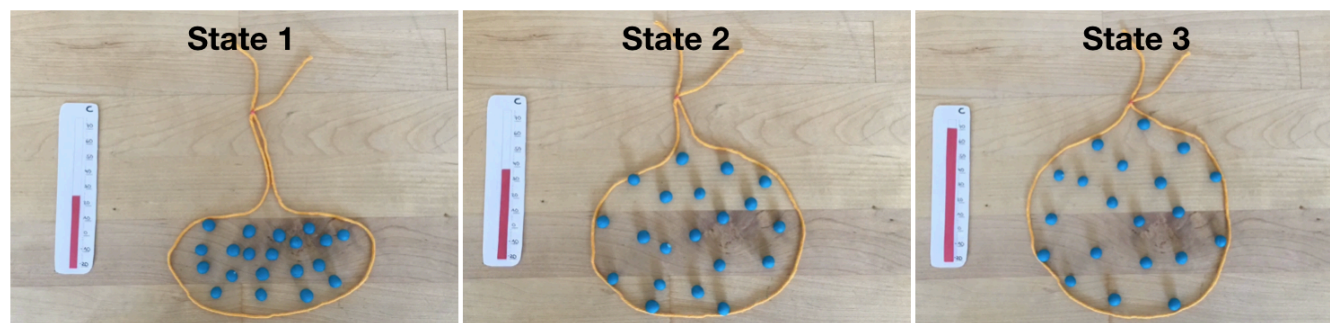
This dynamic visualization can be made with the use of free apps such as Keynote for iOS or
155 PowerPoint. There are also pay-for apps, such as “Explain Everything”, which run on iOS and Android
devices that can also be used to create animations as an interactive board.

Another option for creating visualizations are self-made, stop-motion videos with the app “Stop-
Motion”, that is available for iOS and Android. Stop-motion videos can be described like a self-made
flick book. The students take single pictures, line them up and let them run in a certain frequency.
160 When a stop-motion video is created to explain a chemical reaction at the molecular level, three steps
should be visualized (as shown in figure 1):

Step 1: The starting position prior to the reaction. In general, a single picture of the reactants is
sufficient.

Step 2: The progression of the chemical reaction on molecular level should be visualized step by step
165 with 10-15 pictures.

Step 3: The final state after the chemical reaction. Again, a single picture of the products is
sufficient.



170 *Figure 1 Three out of 85 frames of a student made StopMotion*

At this point, it is possible to give the learner free access to various particle representations. Thus, one
can use either prefabricated elements or let the students become creative in the design of their own
representations. This gives students the opportunity to reflect on the symbolic level by means of their
own learning products. For a two-dimensional visualization, paper clips, colorful cardboard or even
175 moss rubber plates may be used. For a (haptic) three-dimensional visualization, ready-made models
built from molecular building blocks may be used or the students can build their own molecules. For

example, a combination of toothpicks with kneaders or pulp balls is suitable for this purpose.

Interestingly, the latter approach includes the possibility of reflecting different concepts of the reality of the appearance of particles (e.g. in case of the simple particle model in the initial teaching) or ideas
180 concerning the repulsion between electrons (e.g., in case of the differentiated atom).

The explanation of the processes on the molecular level can be implemented on the one hand with embedded text fields and on the other, with accompanying commentary. The latter is a good opportunity for the promotion and evaluation of communication competence, whereby the technical language used by the students is observed. To create stop motion videos, the free app "StopMotion
185 (Studio)" is available for iOS and Android.

Place of action: Chemistry class

However, EXPlainistry is not intended to replace the traditional write up in chemistry teaching. Rather, it offers advantages both in the preparation and also in the consideration of the experiment. In
190 our experience, the format is particularly appropriate when individual groups of students learn in different groups. Here, the possibility can be given to pursue your own interests, but still be able to present your individual results to fellow students. This format can not only be applied to student experiments, but also be useful for demonstrations and teacher experiments. In this case, the teacher performs the experiment then gives this video sequence to the students in order to let them create the
195 first and third part of the EXPlainistry.

For the preparation of an EXPlainistry, a maximum group size of about 3 to 4 students has proved to be beneficial in our teaching observations, because all participants can be actively involved in the development process of the video and the actual experimentation. To prepare and create the videos, scheduling a session of approximately two hours is advisable.

200 In order to learn the technical handling of the devices or apps, the format EXPlainistry, just like a classic protocol, should be introduced and practiced in a joint project. It has proved useful to organize this phase as a competition among the students, by having them create an EXPlainistry to the same experiment. In this competition, a large number of visualization options are created, which are jointly evaluated afterwards. In this introductory phase, however, the focus should be on a professionally

205 clean and correct implementation of the three steps, especially on the visualization in the third, and
less on a media firework, so that the format does not miss its professional-inimical purpose. Our
experience has shown that students need less time to learn how to use the required apps than the first
time to visualize them. In this respect, students should be given sufficient time to consider the
advantages and disadvantages of various visualization options.

210 We experienced within the multiple use of this new method in different schools, that the first time
EXPlainistry is included in chemistry class, students need a clear structure they can follow. Figure 2
shows the procedure of the method. Before the EXPlainistry format is performed independently by
students, the separate sections should be discussed and practiced together step by step by students
and teacher. Phase 1 describes the planning phase. It explores the relevance, implementation and
215 explanation of the central experiment. This part is one of the most important sections as careful
planning is a prerequisite. Once this first phase is completed, the actual experiment is visualized. This
means that the students either experiment on their own or observe the teacher's demo experiment. No
matter the form of presentation, the experiment ~~is~~ should be recorded with the (tablet) camera and
saved for later processing. In the third section, the explanation of the previously recorded experiment
220 will be presented in an understandable way. By selecting a suitable model, students should visualize
the explanation and dynamize it.

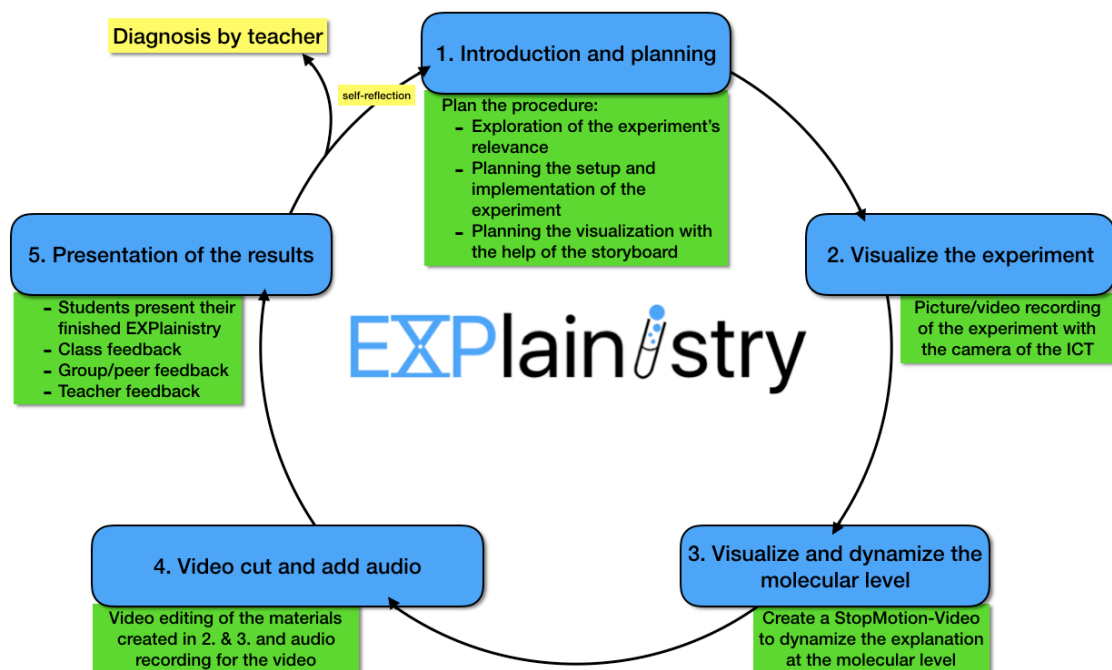


Figure 2 Procedure of the method EXPLAINistry

In the fourth part of the cycle, the videos created in phase 2 and 3 are now to be cut together to form a video. In addition to the technical content, further media skills are to be promoted. In addition to the video editing, an audio track will also be stored, so that students will not only have to visualize the experiment and the particle level, but also verbalize them. The video's audio serves two additional purposes: (1) students are required to reflect and find a creative way to present new subject matter in their own words; (2) it allows teachers to make an initial diagnosis and correct any misconceptions early on in the process, due to additional statements picked up by the recording device. In the last phase, each group individually presents its finished EXPLAINistry to the class, which allows for immediate constructive feedback from the classmates as well as their teacher. This feedback initializes further processes. On the one hand, students are given the opportunity to reflect on their individual work and correct it if necessary. On the other hand, the videos give teachers a product on which a comprehensive diagnosis of the student's performance can be made.

EXplainistry as a diagnostic tool

240 An important part of a teacher's work is the diagnosis of learning progress and misconceptions of students. This format provides teachers with a powerful tool for diagnosing misconceptions. For example, the students' videos can be used by the teacher to give differentiated help and correct individual misconceptions. In class, it is possible to use the method to diagnose learning states before a series/sequence of lessons in order to check the learning condition of the group.

245 The EXplainistry can also be used after the end of a series to check and reflect the learning success. It is even more effective if a video is created by the students before and after the session, as this can lead to a comparison of individual learning success. This comparison can be used by the teacher for control purposes as well as for correction after the session. On the other hand, the students can observe and reflect on their own learning success.

EVALUATION OF THE EXPLAINISTRY

250 Over the past two years the method EXplainistry was used and tested in different school and university classes and teacher workshops. By the help of interviews and questionnaires, we evaluated this format with students, student teachers and teachers to measure their willingness to use this method in their classrooms and how their experience in the academic subject and their learning about
255 and teaching with ICT has grown over time.

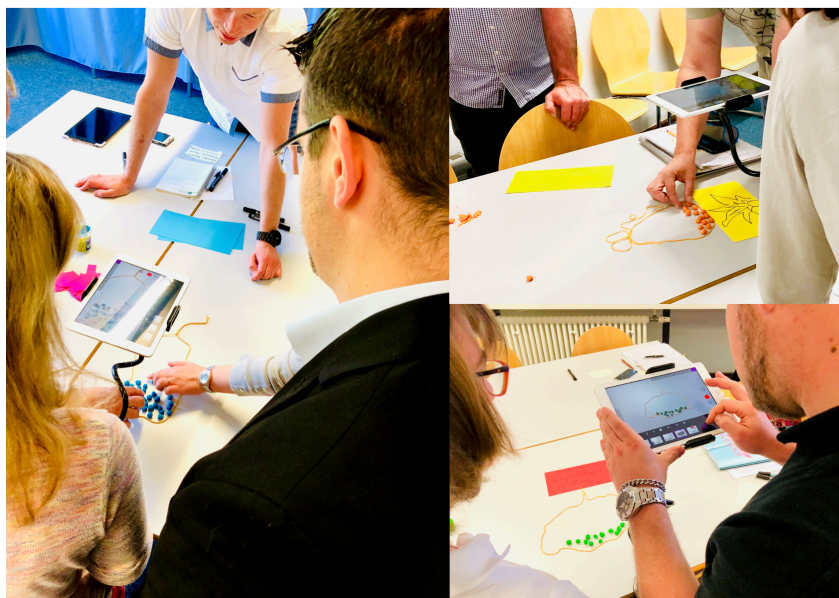


Figure 3 Impressions of teacher workshops

The method was presented to a total of 52 teachers, 24 student teachers and 128 students. However, only teachers and student teachers were included in the evaluation. In our teacher workshops, particular attention was paid to the technical implementation, the didactic added value and the diagnostic possibilities offered by EXPLAINistry.

Figure 3 shows impressions from our teacher seminars. In two consecutive workshops, the method was first learnt technically and then, in another unit, the added values, advantages and disadvantages were discussed further. Within one semester, students had to create one to three EXPLAINistry themselves and present them as project product at the end of the semester. All in all, a total of 76 teachers or prospective teachers were interviewed over a period of 2 years with the help of a questionnaire.

Table 1. Comparative Survey Results for Category 1 on the Benefits and Use of EXPLAINistry

Statement Items for Response	Response Scores ^a by Item, %						Mean Scores (N = 52)	SD
	0	1	2	3	4	5		
1.1 The EXPLAINistry is a good format for documentation of experiments.	3.40	3.40	0.00	17.24	58.62	17.24	3.759	1.091
1.2 The EXPLAINistry is a good format for visualization.	3.40	0.00	0.00	10.34	62.07	24.14	4.000	0.964
1.3 EXPLAINistry adds value to my teaching.	6.90	3.40	3.45	27.59	51.72	6.90	3.345	1.233
1.4 I will use the EXPLAINistry format in my lessons in the future.	3.40	0.00	3.45	27.59	55.17	10.34	3.621	0.979
1.5 EXPLAINistry allows a higher student activity.	3.40	0.00	0.00	13.79	44.83	37.93	4.103	1.047
1.6 The EXPLAINistry allows an analysis of faulty model ideas.	3.40	0.00	0.00	27.59	58.62	10.34	3.690	0.930
1.7 The EXPLAINistry can help me as a teacher to diagnose difficulties in the practical execution of experiments.	6.90	3.40	3.45	27.59	51.72	6.90	3.345	1.233
1.8 The EXPLAINistry can help students to reflect on their own learning processes.	3.40	0.00	0.00	17.24	68.97	10.34	3.793	0.902
1.9 EXPLAINistry can help students who are otherwise quiet to participate in the lessons.	3.40	0.00	0.00	20.69	58.62	17.24	3.828	0.966
1.10 The use of EXPLAINistry makes it easier for students to understand the relevance of the topic they are dealing with.	3.40	0.00	13.79	44.83	34.48	3.45	3.172	0.966
1.11 The EXPLAINistry can be used for performance assessment.	3.40	0.00	3.45	24.14	48.28	20.69	3.759	1.057

1.12 The EXPlainistry makes it possible to promote cognitive learning processes in the classroom.	3.40	0.00	0.00	10.34	86.21	0.00	3.759	0.786
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^aA five-step interval scale was used: 1 = Does not apply at all; 2 = Does not apply; 3 = Neutral; 4 = Does apply; 5 = Does apply entirely. Unanswered questions were scored as 0.

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With the help of this statistical evaluation, it can be said that the EXPlainistry format has consistently received positive feedback from the participants in each item of Category 1, shown in table 1. All averages from this category are between three and four, which means that the participants agree on average on each item of the given statements, up to absolute agreement.

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Table 2. Comparative Survey Results for Category 2 on the Participants' Perceived Competency in Using EXPlainistry

Statement Items for Response	Response Scores ^a by Item, %						Mean Scores (<i>N</i> = 52)	SD
	0	1	2	3	4	5		
2.1 I am good at creating learning videos or animations for my lessons.	3.45	0.00	13.79	24.14	51.72	6.90	3.414	1.053
2.2 I know what to do if I want to explore science phenomena or processes in class using digital video analysis.	3.45	13.79	27.59	31.03	10.34	13.79	2.724	1.334
2.3 I can guide students through the creation process.	3.45	0.00	10.34	27.59	41.38	17.24	3.552	1.121
2.4 The use of EXPlainistry in the classroom motivates me.	3.45	0.00	0.00	24.14	65.52	6.90	3.690	0.891
2.5 Through the use of EXPlainistry, I am more privately involved with video editing.	3.45	3.45	6.90	24.14	58.62	3.45	3.414	1.053

^aA five-step interval scale was used: 1 = Does not apply at all; 2 = Does not apply; 3 = Neutral; 4 = Does apply; 5 = Does apply entirely. Unanswered questions were scored as 0.

280

About the same result as for category 1 can be observed for category 2 (see table 2). All mean values here are between three and four, so that positive feedback can also be inferred from four out of five questions on one's own competence assessment. Item 2.2 asks about the state of knowledge regarding the creation of such a video and shows a slight negative tendency with an average value of 2.724. This can be traced back to a time component. The duration of the individual workshops was about two hours, which were filled with a lot of input. Therefore, the technical practice of the method was short and leads to a slight uncertainty of the participants in their own implementation. This uncertainty,

like any other new method to be learned, can be remedied by practice, which for us is not a negative
285 but a natural phenomenon.

In the context of the evaluation described above, the EXPLAINistry format was also tested with
students. Five different classes from five different schools participated. The content introduction, as
well as the technical aids, were carried out by our team while the present teacher was there to advise
the students. Experience from this test phase has shown that all classes were highly motivated to
290 complete their own videos. Further statistical studies will follow soon.

EXAMPLE OF AN EXPLAINISTRY: CHANGE OF STATES OF MATTER: EVAPORATE VS. CONDENSATE

As already described above, many chemical reactions consist of dynamic processes. The example
295 described in the following is based on the problem of representing dynamic processes on an analog
board. The example describes the consideration of the aggregate states liquid and gaseous and also
deals with the transition from one state to the other. Thematically, the simple particle concept is to be
developed and thus an explanation at molecular level for the experiment is to be found.

- Part 1 (Relevance): Students discover the relevance of the circumstances as evaporation and
300 condensation are everywhere around us. For evaporation and condensation, an example from
daily life could be boiling water in the kitchen and condensation on the lid of the pot.
- Part 2 (Experiment): In an experiment performed by students themselves, 5 milliliters of
acetone are placed in a freezer bag which is then sealed with as less air as possible. The bag is
placed first in a pot with warm, then in a pot with cold water. It can be observed that it initially
305 expands, and less liquid is visible in the bag. In the cold water it shrinks back to its original
size. For control, the volume of the liquid can be measured after the experiment.
- Part 3 (Visualization on a molecular level): The students simulate the experiment on particle
level. For example, balls of clay can be used to simulate acetone particles. With the help of a
StopMotion video, the particles can now be "brought to life". Individual static images, which
310 only represent snapshots, are cut together and become a motion. Thus, the different physical

properties, such as speed and distance of the particles, can be simulated during condensation and evaporation.

ADDED VALUE FOR LEARNING

For students as recipients, EXPlainistry can perform similar functions as explanatory videos
315 from the internet.¹⁸ In addition, it offers the possibility to critically reflect on how the visualization of
an experiment compares with the reality of performing an experiment in the laboratory.

For teachers, EXPlainistry is a valuable diagnostic tool for recognizing inappropriate notions of
the learner. For example, technical inaccuracies or errors in how the students have represented a
chemical reaction at the molecular level can be directly diagnosed in class rather than retrospectively
320 as is the case in traditional post-class marking with delayed feedback. Thus, the immediate playback
and critical assessment of the videos made by the class to the same class is itself a learning
opportunity.

To conclude, we suggest that the combination of ICT-based tasks – documentation, explanation
& visualization – included in EXPlainistry can lead to better learning experiences and outcomes.

325 ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI:

Storyboard for EXPlainistry (.PDF).

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