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An Exploration of How Multimodally Designed Teaching and the Creation of Digital Animations can Contribute to Six-Year-Olds' Meaning Making in Chemistry

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Abstract: Previous research shows that pupils' participation in educational activities increases when they are allowed to use several forms of expression. Furthermore, digital media have become increasingly prominent as "carriers" of meaning in chemistry education. Based on that, this paper aims to explore 'what is happening' and 'what is possible' when six-year-old pupils participate in multimodally designed learning activities and create digital animations of water molecules and phase changes of water. This study is qualitative and draws on the frameworks of social semiotics and Designs for Learning, DfL, where teaching and learning are seen as a multimodal design. The Learning Design Sequence model, developed within DfL is used as a basis for the lesson design and as an analytical tool. The analyzed data were generated by filming when pupils participated in multimodal learning activities, created digital animations, and participated in meta-reflective discussions regarding their digital animations. The main findings are that multimodally designed lessons can increase pupils' meaning making in chemistry, that the creation of digital animations may both increase pupils' participation and support their meaning making, and that meta-reflection of pupils' representations is an important part of the lesson design.

Keywords: chemistry education; design for learning; digital tools; multimodality; pupils' participation

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1. Introduction

Previous research shows that pupils' participation in learning activities increases when they are allowed to use several forms of expression, i.e., when they participate in multimodal activities [1]. While there is extensive research on pupils' and students' learning and learning challenges with the representations used in science education, what and how pupils learn when they create multimodal representations are still relatively emergent research areas [2,3]. To fill this gap, this study aims to explore 'what is happening' and 'what is possible' when pupils participate in multimodally designed teaching and create multimodal digital animations of water molecules and phase changes in water.

Digital media have become increasingly prominent as "carriers" of meaning in chemistry education; for example, see [4]. Furthermore, the Swedish curriculum for preschool class states that all pupils should be given the opportunity to develop their ability to use digital technology, for example in connection to problem solving, communication and learning [5]. Many six-year-olds use digital tools for social communication and for gaming [6] but an identified educational problem is that such experiences and knowledge are not

always recognized or the basis for continued learning in school [7,8]. Further, not all children have access to digital tools at home and do not have the same opportunities as other children to develop digital competence [9]. Consequently, the school plays an important role in giving all children the opportunity to use digital tools and gain digital competence.

In this study, the pupils use digital technology to create their own animations of water molecules after participating in multimodally designed learning activities. Halverson [10] suggests shifting research perspectives regarding the use of digital tools in teaching and learning from 'what works' to 'what is happening' and 'what is possible'. This suggestion is acknowledged and applied in this study, since it opens for reflections on what education might look like and consist of when digital tools are used when pupils create multimodal texts in science in explorative ways.

The following research question is explored:

- What happens and what is possible when six-year-olds participate in multimodally designed learning activities and create digital animations in chemistry?

1.1. Semiotic Resources in Chemistry Education

Chemistry can be defined as the scientific study of the properties and behavior of matter. Hence, chemistry is all around us. Arguably then, everybody should have a basic understanding of chemistry to be able to make informed decisions regarding important aspects of our lives and the world we live in, for instance decisions regarding our health and the environment. It is also highlighted in the Swedish curriculum for 6-year-olds that the teaching in preschool class should cover core content, such as "[c]hemical and physical phenomena that are familiar to the pupils, for example the transition from ice to water" [5] (p. 24).

However, chemistry is experienced as challenging, both for teachers to teach and for pupils to learn; for example, see [11–13]. One suggested explanation of this challenge is the fact that many chemical processes and phenomena cannot be observed with the naked eye and are therefore not part of pupils' everyday life. For instance, it is possible to see that an ice cube is melting at a macroscopic level, but the chemical explanation, at a submicroscopic or representational level, is not directly visible, i.e., how the water molecules absorb energy when the temperature is rising, and how that increases the molecules' movement, which, in its turn, leads to the breakages of the intermolecular bonds. Visual representations can be used to represent chemical phenomena at submicroscopic and representational levels to make the "invisible" chemistry phenomena visible (for example, see Figure 1). But these representations are often challenging for pupils to use for making meaning, thus pupils do not always experience these representations in the way that the teacher intends or assumes; for example, see [14–16].



(**a**) (**b**)

Figure 1. Two different ways of representing a water molecule. In (**a**), a water molecule is presented as a space filling model. The red "ball" represents an oxygen atom, and the white "balls" represent hydrogen atoms. In (**b**), a representation of a water molecule's molecular formula is presented. The letter "H" symbolically refers to the hydrogen atom, the number "2" refers to the number of hydrogen atoms in the molecule, and the letter "O" symbolically refers to the oxygen atom.

However, when pupils increase their understanding of scientific phenomena, by "seeing" what is not directly visible, it affords new meanings to their everyday experiences [17]. Therefore, in order to make sense of the world around us and communicate about these

phenomena and processes that we are unable to observe directly, various semiotic resources need to be used [18].

In this study, we draw on a social semiotic perspective on multimodality and use Van Leeuwen's broad definition of semiotic resources, defined as:

> . . .the actions and artefacts we use to communicate, whether they are produced physiologically—with our vocal apparatus; with the muscles we use to create facial expressions and gestures, etc.—or by means of technologies—with pen, ink and paper; with computer hardware and software; with fabrics, scissors and sewing machines, etc. [19] (p. 3).

Furthermore, in chemistry education (and in all communication and meaning making), different modes need to be used [18,20–22]. The term mode is defined by Bezemer and Kress [4] (p. 171) as "a socially and culturally shaped resource for making meaning". Examples of different modes used in chemistry education are verbal and written language, mathematics, drawings, graphs, diagrams, physical models, and animations. For a semiotic resource to be referred to in modal terms, the mode in question needs to have a set of resources and organizing principles that are recognized within the specific context of usage; for example, see [23]. This means that different modes afford different intrinsic meaning potentials. Different modes can therefore bring different aspects of a phenomenon into focus, and thus significantly influence the meanings that can be made [18,24]. For example, the movements of water molecules can be shown with an animation, while, for instance, a static diagram is less apt for showing movement. If a static diagram would be used when molecular movement is a critical aspect, then it needs to be unpacked, for instance by using verbal language, bodily actions, and/or an additional visual representation in order for the pupils to discern movement as a critical aspect. Thus, which semiotic resources that are made available by the teacher and how these resources are unpacked in the classroom affect pupils' and students' meaning-making possibilities [25,26]. Furthermore, there is an agreement in the chemistry education literature that pupils and students need to be able to use functional modes to communicate their intended meanings appropriately; for example, see [20,27–32]. Also, pupils' communication and meaning making with different modes give them various opportunities for participation and can hence function as a way to equalize the opportunities for participation and meaning making [33]. Thus, the use of different modes makes it possible for more pupils to create meaning, even if they, for example, do not have Swedish as their mother tongue or have specific language impairments. Thus, there is a recognition of the need to study how different kinds of modes are combined into an integrated, multimodal whole—for example, see [23]—to support all pupils' meaning making.

1.2. The Creation of Digital Animations

Research suggest that pupils' meaning making is supported when they are given opportunities to create their own representations in science; for example, see [34–36]. By creating their own representation of a chemical phenomenon, pupils may also interpret their representations and how they coheres with their intentions and ideas [37]. Prain and Tytler [34] (p. 2757) claim that the representations created by pupils can be "understood as enacting science learning and reasoning because this kind of activity is consistent with how knowledge is developed and communicated in the science community".

In a previous research study, Fleer and Hoban [17] showed how preschool children through the co-construction of a simplified form of a stop-motion animation (Slowmation) developed their scientific reasoning and were able to make links between their experiences in everyday life and scientific phenomena. The results in their study also showed that when the children watched the animation together, more questions and discussions arose. Fleer and Hoban [17] drew the conclusion that watching the animation together supported the children's conceptual development. The authors also drew the conclusions that making an animation helps children to express what they had learned, since actions and thoughts

could be expressed in a visual product, which is then a way to make the children's ideas and theories visible also to others.

In this study, the pupils both construct molecules with ball and stick models and create digital animations to express their understanding of water molecules and the phase changes of water. Furthermore, they watch and discuss their animations together with their peers.

1.3. Designs for Learning Theory and the Learning Design Sequence Model

This study builds on the designs for learning theory [33,38] and it is theoretically framed within a social semiotics perspective of multimodality [39], which entails a view on teaching and learning as a form of multimodal design [33,38]. From this perspective, teachers' choices in a teaching and learning unit can be described in terms of designs for learning. In the same vein, pupils' choices can be described in terms of designs in learning [38,40,41], where they make choices among available resources in their meaning-making process. According to Selander [38] (p. 12):

> the concept of "designs for learning" highlights the material and temporal conditions for learning as well as the learning activity itself. The use of modes and media in processes of interpretation and identity construction is here central for the understanding of learning activities.

From the designs for learning perspective, meaning making is understood as a process of interpreting and producing semiotic resources, or signs, and learning is defined as a manifest change in pupils' sign making [38]. As one cannot know whether learning has actually taken place, one can only note 'signs of learning', for instance if a pupil who was previously unfamiliar with the concept 'molecule' starts using the term in disciplinary relevant ways.

In this study, the Learning Design Sequence model (LDS model) [40] (Figure 2), developed within designs for learning, is used both as a tool for planning learning activities, and as an analytical tool. The model consists of three main parts, (i) framing and setting, (ii) the primary transformation unit, and (iii) the secondary transformation unit. These three parts are presented briefly below.

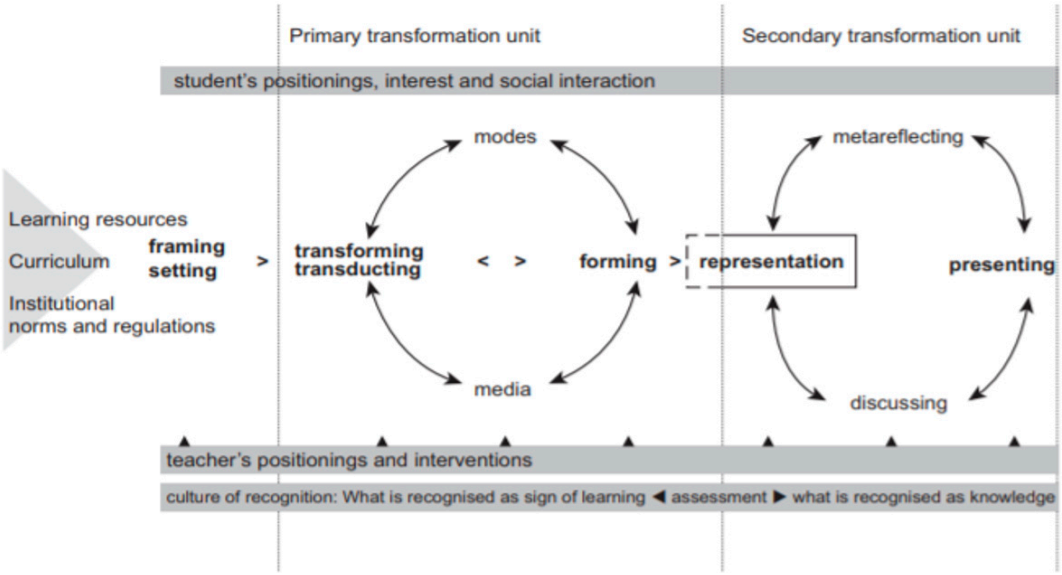


Figure 2. Learning Design Sequence model (from [40] Figure 1.3 p. 4, used with permission from the authors).

There are certain premises (framing) that affect teachers' choices in their teaching and learning activities. For instance, curriculum documents, institutional norms and regulations

have an impact on teachers design of such activities. Thus, the teacher has a purpose with the planned activities and the resources that are made available. Based on these premises, the teacher introduces the activities, or in other words, "sets the scene" (setting). In the primary transformation unit, pupils engage in different activities using available resources and they transform or transduce content through different representations. Transformation relates to the movement of meaning between different semiotic resources within the same mode—see [4]—for example rewriting text from a textbook. Transduction, on the other hand, concerns a movement of meaning between semiotic resources in different modes, for example from a written text into a digital animation [33].

The primary transformation unit can consist of a number of cycles, when pupils make meaning about the content in various ways, and it can result in pupil-created representations (e.g., a written, visual, or spoken text) meant to communicate with others. Hence, creating representations of different kinds during the primary transformation unit is a way for the pupils to make meaning about the content, and also to share their experience with others, often the teacher or classmates.

In the secondary transformation unit, pupils' representations, and the learning activities that they participated in during the primary transformation unit, are in focus for pupils' and teachers' meta-reflections. Teachers are assumed to continuously assess pupils' ongoing learning process, throughout the whole learning design sequence. Thus, what counts as valid knowledge is an important aspect in the theory Designs for Learning.

2. Methods

In the following, a description of the participants, the setting, the ethical considerations, the data collection, and the analytical methods applied in this study will be presented.

2.1. Participants, Settings, and Ethical Considerations

This study was conducted in a culturally and linguistically diverse school in a small Swedish town, with approximately 50% of the pupils learning the language of instruction (Swedish) in parallel with learning the subject content.

We applied purposive sampling when selecting the participating classroom teacher since the focus was to sample participants in relation to the posed research questions, in a strategic way [42]. A teacher who had participated in one of our previous studies [43] served as a gatekeeper [44]. She put us in contact with preschool class teachers who were interested in designing lessons in line with the focus of this study. The participating teacher wanted to be a part of this study, as she viewed her participation as a possibility to develop her own teaching practice. The classroom teacher is an experienced preschool teacher specialized in teaching in preschool class.

Data were collected in the teacher's preschool class (six-year-olds) consisting of 19 pupils. All the pupils and their caregivers were asked if the pupils could participate in this study, and 12 pupils (7 girls and 5 boys) consented to participate in this study.

This study adheres to the ethical considerations regarding informed consent, anonymity, the right to withdraw participation from this study without giving a reason, and that the data would not be used for other purposes than those stated in the letter of information [45]. The authors formulated the letter of information and the first and second author participated at a parent's meeting to talk about this study, to answer questions, and to distribute the letters of information. All the caregivers of the participating pupils signed an informed consent. However, when children are participants, there is a need for researchers to critically reflect over ethical issues at all stages of the research process [46,47]. For example, when data were generated in the classroom, the teacher divided the class into groups where the non-participating pupils were placed so they would not be captured on film.

To ensure consent from the participating pupils throughout this study, the first and second author continuously asked them if they wanted to be filmed before recording, since there are a variety of aspects to critically consider before undertaking video recording. For example, how to deal with moral and ethical issues that might occur when collecting

permanent records of what children say or do [48,49]. Therefore, the first and second authors were sensitive and paid particular attention both to the pupils' verbal and non-verbal communication to ensure genuine consent to participation. One participating child expressed that he did not want to participate in the group interview, so he stayed with the other pupils in the classroom.

2.2. Data Collection

The classroom teacher and the first author discussed the design of the three chemistry lessons focusing on water molecules and phase changes of water, using the LDS model as a basis and with a particular emphasis on what modes and resources to make available for the pupils to use in their meaning-making process. In the first lesson, the teacher introduced water molecules, aggregate states of water, and phase changes of water in a variety of ways. This lesson was video recorded, using a tablet on a tripod. In the second lesson, the process when the participating pupils in pairs or small groups created digital animations by using a digital application was also recorded through video-recordings with tablets on tripods, which were placed with each of the four groups. Thereby, sets of data were generated that captured fine-tuned details of the pupils' actions and their interactions during the process of creating digital animations.

Video-Stimulated Recall Interviews in Pairs and Groups

Video-stimulated recall involves recording an activity, here a digital animation, and then replaying the recording to the participants so that they can comment on aspects of interest [50]. These aspects can be chosen either by the researcher or the participants or by both, as was the case in this study. The children's comments on their digital animations and the creating process turned out to be a fruitful way of generating data and capturing signs of learning. In that sense, the interviews could be seen as the secondary transformation unit in the LDS model. The video-recall sessions were also video-recorded with a tablet on a tripod, which made it possible to capture and interpret the pupils' multimodal communication.

Instead of staging a more fixed interview setting with ready-made questions only, the aim with the video-stimulated recall interviews was to encourage the pupils to comment on what they had done, and to comment on their intentions behind their digital animation. This was done to support the pupils to better recall how they had reasoned during a specific episode—for example, see [51–54]—in this case how they reasoned when creating the digital animation. However, to be able to have qualitatively fruitful discussions with children, one needs to shift towards engaging with children's own cultures of communication [55]. Since young children often play with toys like stuffed animals, we decided to use Affe the monkey and let him "talk" to the pupils and "ask" them questions (see Figure 3). We chose to conduct the video-stimulated recalls in pairs and in small groups as a way of making the children feel comfortable and safe together with someone they knew. Another reason for this choice was to make sure that each pupil would have at least one peer to interact and discuss their experiences with. Hence, this was a way of creating a comfortable and productive context for the interviews, and it is also reduced the asymmetry of power between the interviewee and the interviewer [56].

The video-stimulated recall interviews were conducted twice. The first time was during lesson 2 (see Table 1), where each of the participating groups of pupils were interviewed separately, in a separate room, familiar to the pupils. They watched and discussed their animation, and both the interviewer and the pupils could control the tablet and pause it when they wanted to comment on aspects of interest. The pupils were also asked questions regarding their selection of representations in the animation—what they represented, why they chose the specific representations, and if they would like to change anything in the animation. They were also asked if they had learnt something they did not know before the lessons and what they felt about making an animation representing their experience. In this way, the pupils were given the opportunity to discuss both the task of making the animation and the chemistry content.

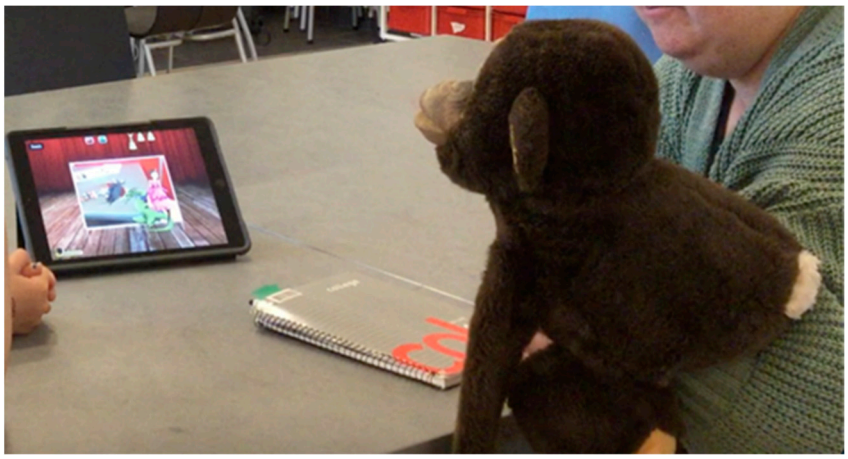


Figure 3. Affe the monkey asks questions about the pupils' reasoning when creating their digital animation.

Table 1. Overview of collected data. Altogether, 2 h, 34 min and 19 s of video recordings were captured.

Lessons	Video Recordings
Lesson 1. Teacher's introduction	Recording from tablet on tripod, 22.09 min
Lesson 2 Pupils creating a digital animation (video observations) and talking about their digital animation (video-stimulated recall interviews)	Recordings from tablets on tripods: Pupils creating a digital animation. Group 1: a girl and a boy 25.02 min Group 2: two girls 12.06 min Group 3: two boys 17.24 min Group 4: two girls and a boy 32 min Total: 1 h 26 min 32 s Recordings from video-stimulated recall interviews: Group 1: a girl and a boy 6.41 min Group 2: two girls 9.28 min Group 3: their digital animation was not saved. Group 4: two girls and a boy 5.43 min Total: 21 min 52 s
Lesson 3 Pupils watching all the digital animations and talking about them (video-stimulated recall interviews)	Recordings from video-stimulated recall interviews: Group 2 and 3: two girls and a boy (one of the boys in group 3 did not want to participate) 12.22 min Group 1 and 4: three girls and a boy 11.33 min Total: 23 min 55 s

The second time video-stimulated recall interviews were conducted was the following day, during the third lesson. This time, the pupils watched and discussed all three groups' digital animations in bigger groups. Thus, these video-stimulated recall interviews were conducted in a similar way as before, but with the larger groups, so that the pupils were given the opportunity to watch and discuss the other groups animations and talk with each other and the interviewer about the animations, water molecules and the phase changes of water. For instance, they were asked if they learned something new by watching and discussing their peers' animations, and why they thought the animations were different from each other. We chose to have two groups together instead of one bigger group with all the participating children, so that all the children were given greater opportunities to express their opinions and their meaning making.

2.3. Analytical Methods

The data were analyzed through the learning design sequence model (Figure 1), presented above. The analysis was multimodal in nature and focused on the teacher's design for learning and the pupils' design in learning. We regard all three lessons as one learning design sequence. The pupils' design in learning is based on what happens during all the lessons along with the video-stimulated recall interviews where the pupils also learned from each other while discussing their animations.

The data analysis was inductive-interpretative in nature and the analysis begun with the first and second author watching the recorded videos several times. The analysis continued with a transcription of the spoken language in the recordings, combined with still-images and comments of gestures, gazes, and other resources used. The first and second author then read through the transcripts repeatedly in order to identify the parts of the data corpus that involved instances relevant for answering the research question. These extracts from the transcribed material formed the data set for further analysis.

After reviewing the data set in detail, the data were analyzed through the learning design sequence model, presented in Section 1.3 above. The analysis was focused the teachers design for learning, the pupils design in learning and signs of learning.

3. Results

To answer the research question, this section includes results regarding what happened and what was possible when six-year-olds participated in multimodally designed learning activities and created multimodal digital animations in chemistry. The results are presented sequentially in line with the Learning Design Sequence model.

3.1. Framing and Setting

As previously mentioned, the school where the learning design sequence was carried out is of multicultural and multilingual nature. Therefore, all teachers have jointly decided to use visual support as a learning resource. This choice is based on the idea that the use of visual resources can function as a support in pupils' meaning making about content as well as supporting pupils' when learning the language of instruction (Swedish). The Swedish curriculum for preschool class [5], which states that the teaching in preschool class should cover phenomena in science that are familiar to the pupils, was used as a basis for the learning activities. In this study, the focus was phase changes of water and the structure of water molecules.

The physical classroom made it possible for the teacher to gather and group the pupils in different ways. Among the available physical resources in the classroom were a smartboard, a class set of tablets and a small kitchen including a stove, a freezer, and a sink. To set the scene at the beginning of the first lesson, the teacher held a tray with cups containing water when the pupils entered the classroom in order to arouse their curiosity for the upcoming project.

3.2. The Primary Transformation Unit

In the primary transformation unit, the pupils engaged in different activities using available resources and transforming or transducing the disciplinary content through different representations. In this learning design sequence, a variety of learning activities were carried out in order to afford the pupils, including those who are not fluent in the language of instruction, a more holistic understanding of water. Each activity below is regarded as one cycle in the primary transformation unit.

3.2.1. Activity 1—Tasting Water to Arouse Curiosity and Connect to the Pupils' Everyday Experiences

The teacher began the first lesson with letting all the pupils taste liquid water and asking them how the water tasted, that is, exploring the phenomenon at a macroscopic level. Several of the pupils answered the teacher's question regarding the taste of water by

saying, for example 'wet' and 'good'. In this activity, the liquid water was a resource which enabled the pupils to reflect on and verbalize their experiences of drinking water. In this way, the teacher introduced the subject area in a way that aroused the pupils' curiosity and, at the same time, it enabled the teacher to explore the pupils' previous experiences. One of the pupils asked why they were given water, and another pupil answered: 'Because we are going to work with it (water)'.

3.2.2. Activity 2—Exploring the Submicroscopic Level of Water with Three-Dimensional Ball and Stick Models

After the water-tasting experience, the teacher added another resource, a ball and stick model of water (see Figure 4), which represented the phenomenon at a submicroscopic level. The following dialogue occurred:

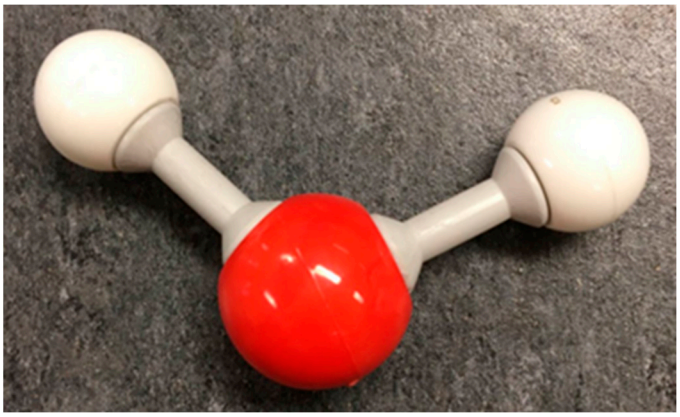


Figure 4. A ball and stick model of a water molecule.

Teacher: 'What do you think this is?'
Pupil 1: 'A thing you make massage [with]'.

From the dialogue above, and the fact that the other pupils did not answer the question shows that they were not familiar with molecular models of water before this lesson. When the teacher noticed this, she illustrated how to build a molecular model of water and, at the same time, she verbally unpacked the representation by saying: 'You take a red ball like this, do you know what this is called?' Several pupils showed commitment and answered: 'No!' at the same time. The teacher explained that the red ball represents an oxygen atom and showed how two white balls could be connected to the red ball with sticks. Suddenly a pupil said: 'You must have oxygen to live'. The answer was confirmed by the teacher who also took the opportunity to explain that we also need water to live. Then, she asked if the pupils knew what the white balls are called, which no one knew, and she told them that they are called hydrogen. She continued by asking the pupils if they knew where they could find water molecules. Several pupils answered: 'In the sea... In water... In ice...'. These answers indicate signs of learning since the pupils made the connection between water at a macroscopic level and water molecules at a submicroscopic level.

The teacher continued by telling the pupils about the size of a water molecule. She lowered her voice and said: 'You know, in one drop of water (raising her little finger to symbolize one raindrop), imagine a raindrop, (many pupils nodding their heads) it is really small. There are more water molecules in one raindrop than there are people in the whole world (making a big circle with her hands)'. The pupils reacted with excitement. The teacher confirmed the pupils' reaction by saying: 'Isn't it cool!' She continued by referring to the first activity by saying: 'Were there any water molecules in the water you drank?' Most of the pupils answered 'Yes!' Again, this indicates that they were able to connect the submicroscopic level (water molecules) with the macroscopic level (visible liquid water).

3.2.3. Activity 3—Looking at Pictures of Water Molecules and Different States of Water to Connect the Submicroscopic Level to the Macroscopic Level

By showing pictures on the smartboard, the teacher introduced a new mode, images. The first picture showed a molecular model of water. When showing it, the teacher asked: 'What is this?' Several pupils answered: 'Water molecule'. This could also be interpreted as signs of learning, since none of the pupils had expressed that the three-dimensional model represented a water molecule when it was first introduced. Other signs of learning could be noted when the teacher asked what the red ball symbolized: 'What is it called?' Several pupils now said that it was called oxygen, in contrast to when they were asked the same question in the second activity, where none of them expressed that the red ball represented oxygen.

The teacher then introduced three states of water by showing pictures of snowflakes (solid), rain (liquid) and steam from a saucepan (gas). The importance of choosing representations from the pupils' perspective became apparent during this activity. One of the pictures showed an umbrella and rain falling from the sky with the text 'FLYTANDE VATTEN' (Eng. liquid water, see Figure 5) and the teacher said: 'Here is water in a different state'.



Figure 5. The picture shown by the teacher was intended to represent water in a liquid state.

However, there were no direct replies from the pupils, so the teacher gave some clues: What is it that falls down from the sky? At the same time, she showed the movement of raindrops with her hands. One possible interpretation of the pupils' silence is that there might have been pupils that were confused by the text because it said 'LIQUID WATER' instead of 'RAIN'.

3.2.4. Activity 4—Exploring the Motion of Water Molecules through a Combination of Modes

In the next activity, the teacher combined resources in several modes: two-dimensional images and three-dimensional molecular models of water, embodiment, and verbal explanations. The teacher repeated that water molecules can be in three states of aggregation (solid, liquid, and gas). To help the pupils to grasp how the water molecules behave in a solid state, the teacher strived to connect this to their bodily experiences while showing a picture of snow and saying: 'How does your body feel when it is winter outside and you are freezing? (taking a rigid posture and hugging herself)'. Then, she showed with her body and with the ball and stick models how the water molecules move in a solid state: 'They get stuck and sit still like this (moving the ball and stick models with small hand movements back and forth in the same place). When you feel cold, you become stiff (showing with her body). So do the water molecules, but if you add some heat (changing to an image of liquid water on the smartboard) then the water molecules start to move [more] (moving the ball and stick models with bigger hand movements)'. Finally, the teacher showed a picture representing gas and said: 'Then they become mischievous and start to move a lot

at full speed (moving the ball and stick models with big and fast hand movements). Now you will act as water molecules, it will be like a physical exercise'. Thus, in this activity, the teacher combined different modes in order to visualize phase changes of water at both a macroscopic and submicroscopic level.

3.2.5. Activity 5—Exploring the Motion of Water Molecules through Bodily Action

Five different modes were used in the following activity: sound, three-dimensional concrete models, images, verbal language, and bodily action. The teacher played the sound of running water (liquid) and asked: 'How do they (the water molecules) move? Can you turn into water molecules?' Then, she started to move at the same time as she showed with the ball and stick models that the water molecules move faster in a liquid state. Then, there was a change in sound, and the teacher said: 'If you now transform and become ice... then you will just freeze where you are'. Since the pupils were already standing still it is difficult to say if they "moved" like water molecules or not in this instance. One of the pupils said: 'I want to be steam (gas)!' This was noted by the teacher who said: 'And then we will become something else (she showed a picture of fog). What does this image show?' Several pupils said: 'Fog!' Most likely it would have been easier for the pupils if the teacher had used the same picture of steam (gas) as in activity 4. Since the pupils did not start moving, the teacher continued by saying: 'Now you are going to move like water molecules when there is steam, how did they move again?' One of the pupils started to move her body a lot and waved with both her arms but was still standing in the same place.

3.2.6. Activity 6—Exploring the Motion of Water Molecules by Watching a Video Clip

During this activity, the teacher showed a short video clip (2.5 min), which can be found on YouTube and is called *Solid, liquid and gas*. In the video clip, four modes were used: verbal language, images, written text, and animations. Initially, three beakers were shown in the video clip, one with ice (solid), one with water (liquid) and one with water vapor (gas). Then, the video clip illustrated how water molecules behave in the solid phase and what happens when a substance melts. Finally, it showed how water molecules move when a substance vaporizes and transforms into a gas state. The video clip then offered the pupils an opportunity for repetition by letting them see, once more, what happens at a submicroscopic level when a substance is cooled from a gas phase to a liquid phase and continues to cool until the substance is in a solid phase again. The water molecules were represented as orange circles, hence an abstract way of representing molecules which often is used at higher school levels. However, these preschool pupils seemed to have grasped most of what was presented in the video clip, probably because they had experienced the phenomenon in different ways in a variety of activities beforehand.

3.2.7. Activity 7—Reconnecting to the Macroscopic Level by Holding an Ice Cube

After they had watched the video clip, the teacher said: 'Now you are going to feel what it is like to have something in your hand'. Some pupils guessed that they were going to hold water in their hands and one of the pupils said: 'Some ice?' When the teacher told them that she had to take it out of the freezer, several pupils shouted: 'Ice!' When the teacher came back with the ice on a tray, a pupil asked: 'Are the water molecules in here?' The teacher confirmed and asked: 'How are the water molecules moving now?' Many of the pupils said that they were still. The teacher ended the activity by telling the pupils that they now have started the project with water and that they will continue the following day, and that they would also use a digital application, which several pupils seemed to appreciate.

3.2.8. Activity 8—Using Previous Resources to Reconnect the Structure and the Movement of Water Molecules

The following day, the second lesson began with a repetition of what the pupils had experienced the previous day. The teacher began by showing a short video clip of liquid

water and asked the pupils what they remembered about water, which can be seen as a way for the teacher to assess the pupils' ongoing learning process. For example, one pupil answered: 'The red one had something to do with oxygen'. The repetition included several of the resources the pupils had experienced the day before, such as the YouTube clip, the ball and stick models and some ice cubes. The pupils held the ice cubes in their hands, and the teacher asked them what they thought would happen with the ice cube when they held it. Several of the pupils answered that it was going to melt. The teacher continued to ask them how the water molecules move when the ice is melting, and one pupil answered that the water molecules' movement will increase. Another pupil stated: 'We have warm hands', as a reason for why the ice is melting. The teacher ended the activity by saying: 'You are now going to work together with a friend, and you will get a box like this (showing the box with balls and sticks). What do you think you are going to build?' As a response several of the pupils yelled: 'Water molecules!' The pupils' answers during this repetition can be seen as signs of learning, indicating that their participation in the multimodal activities the day before had increased their disciplinary understanding of water molecules and their movement in different states of aggregation.

3.2.9. Activity 9—Building with Ball and Stick Models to Explore the Three-Dimensional Structure of Water Molecules

In this activity, the pupils built molecular models with ball and stick models (see Figure 6). The pupils were divided into pairs or small groups and had access to a whole box with balls of different colors (symbolizing atoms) and sticks of different lengths (symbolizing the bonds between the atoms).



Figure 6. A box of balls and sticks. The different colors of the balls represent different atoms.

All of the pupils began to build ball and stick models of water molecules individually, in a disciplinary relevant way, combining red and white balls, similar to the model shown in Figure 4. Since the pupils had not built these kinds of models before, according to their reaction when the teacher first showed them a ball and stick model in the beginning of the lesson, this can also be regarded as signs of learning. After having built disciplinary relevant water molecules, several pupils started to build ball and stick models with other kinds of balls and sticks. Some pupils also started to play with their molecular models. For example, one pupil built a molecular model that looked like a fidget spinner and played with it in that way. Another pupil built a molecular model and said: 'This is the best water molecule. I pretend it is a monster'. In this activity, the pupils were given the possibility to actively explore the available resources which invited them to both play and make meaning of the disciplinary content.

At one point during this activity, one of the pupils showed a sign of learning when he noticed a small puddle of water on the bench he was sitting at. He pointed at the water and said: 'The water molecules move a lot in there'. Then, he picked up two of the ball and stick models of water molecules that he had built and quickly moved them around each other and said: 'Look, the molecules move like this [in the puddle of water]'. This example

shows that the pupil was able to move between and connect the macroscopic level of the phenomenon to the submicroscopic level.

3.2.10. Activity 10—Pupils Creating Digital Animations to Transform the Content and Represent Their Experience

After the pupils had built water molecules with ball and stick models, the teacher said that they, together in the same pairs or small groups, were going to create digital animations in an application which can be used to create your own animations, including a voice-over. In the application, own photos or built-in figures can be used to move around the screen, such as princesses, dragons, birds, and humans. Further, different backgrounds such as a sea, clouds, and a forest can be added. In addition to the tablets with the animation application, other available resources were the molecular models that the pupils had previously built.

The instruction that the pupils received from the teacher was: 'You are going to make a film with your water molecules that you have built. The film should be about what we have learned'. A pupil said: 'Water', which the teacher confirmed and continued by saying: 'Liquid, steam, ice'. Another pupil said: 'Molecules' and the teacher responded: 'Water molecules. You make the movie together in the application, we worked with that last week, remember?' Several of the pupils answered: 'Yes'. The teacher continued: 'So now it is important that you cooperate and make a little fairy tale about this. Has everyone understood the task?' A unanimous 'Yes' was heard from the pupils. The creation of the digital animation afforded the pupils the opportunity to represent the movement of the water molecules in combination with a recorded verbal explanation and other sound effects. In other words, it was possible for the pupils to make a multimodal digital representation of their gained experiences. But even though the pupils, on a previous occasion, had been practicing making a fairy tale using the application, they had not been introduced to inserting photographs. This resulted in the pupils spending some time with practical issues rather than the content. However, the pupils were very engaged in the creation of the digital animations, and in comparison to the activity where the pupils built with ball and stick models, they collaborated much more within the groups when they created the digital animations. There was a combination of play and signs of learning during both the creation process and in the final multimodal representations. One example is when one of the groups were to choose which background to use and one of the pupils pointed out: 'Now we will take one [background] with water', which resulted in a discussion concerning which of the backgrounds that would best represent water. In the final production, this particular group used two different backgrounds that they alternated between, showing that they themselves were able to solve the conflict that arose. Another group used both characters from the application and pictures of their molecular models and inserted them into the application. Through roleplay, they let the characters explain how the water molecules move in different phases. During the group's planning of the animation, one of the pupils said: 'We have to have someone, two like... two girls who describe what water molecules are'. The characters were also used in a playful way in the story, indicating that this task also provided opportunities for playing.

The digital animations varied between the groups. Two of the groups used photos they had taken of the molecular models, while one group only chose to use cartoon characters and backgrounds that were not explicitly connected to water. All the groups did however say the term 'water molecules' in their animations. One of the groups explained in their digital animation how water molecules move in different states of aggregation by moving pictures of the ball and stick models of water while providing a verbal explanation of water molecules' movement through cartoon characters. Another group created a song about water molecules, one of the lines in the song went like this: 'We are water molecules (pictures of ball and stick models of water molecules were moving in front of a background of a sea), in water on our earth'. Again, this illustrates that some pupils were able to connect

the submicroscopic level (water molecules) to the macroscopic level (sea and water on the earth).

3.3. The Secondary Transformation Unit

During the secondary transformation unit, the animations created during the first transformation unit were in focus for the meta-reflections in which Affe the monkey (controlled by the first author) and the pupils participated.

Meta-Reflection

The pupils showed their final digital animation to Affe the monkey and the first author. All the pupils were very excited to talk to Affe. They were told that Affe did not know anything about water or water molecules but that he wanted to learn. Affe asked the pupils questions about their digital animations and about water and the pupils were very engaged in explaining to Affe what they knew and how they reasoned when they created their animations. An example of signs of learning that were expressed in the pupils' discussion with Affe can be seen in the following dialogue:

Pupil 1: 'The film (animation) was about water molecules'.

Affe: 'What is a water molecule?'

Pupil 2: 'It's a thing found in water. That exists everywhere in water'.

Pupil 1: 'Look Affe, what we have done (pointing to the animation)'.

Affe: 'Are all these water molecules?'

Pupil 2: 'Yes, when it gets cold, they (the molecules) sit together. But when it's warm, they move and if you increase the heat, it becomes (making fast movements with her hands)'.

The following day, the pupils talked to Affe the monkey one more time in bigger groups while watching all three groups' digital animations. Together, they discussed the digital animations and if they learned anything new from watching them. During the group discussion, through bodily action, the pupils showed Affe how water molecules move in different states of aggregation, in this way using resources that had been made available in the primary transformation unit. The pupils also were given the opportunity to hold Affe. An example of what happened when a pupil was allowed to hold him was that she said: 'Affe is very warm and cuddly, so the water molecules move very quickly inside Affe'. In this statement the pupil showed that she was aware that water molecules move faster at higher temperatures, and she also expressed that water molecules exists in Affe, even though she did not explicitly see or feel any water in or on him. When the first author asked if Affe contained water, she said: 'Yes, because monkeys drink water'. Thus, the meta-reflection in the second transformation unit made it possible to discern signs of learning.

Another example of what happened during the second transformation unit was when one of the pupils held Affe the monkey and started to ask her own questions to her classmates as if it was Affe the monkey who were asking them. She held Affe close to her ear, pretending that Affe was whispering something to her and said: 'He [Affe] says something... Do they [the water molecules] have ears or mouths or noses?' The pupils jointly concluded that the water molecules do not. Through this playful approach, the pupils were able to ask questions as if it were someone else who was wondering, which may have made it easier for the pupils to ask questions that they otherwise might not have dared to ask.

4. Discussion

In this study, we set out to explore what happens and what is possible when six-year-olds participate in multimodally designed learning activities and create multimodal digital animations in chemistry. The main findings are that a multimodal design can increase pupils' meaning making in chemistry, that the creation of digital animations increase pupils'

participation in the activity and support their meaning making, and that meta-reflections about pupils' representations is an important part of the lesson design.

4.1. A Multimodal Design can Increase Pupils' Meaning Making in Chemistry

As presented in the results, several signs of learning were noted in the video-recorded activities, for example during Activity 9, when a pupil was able to describe the movement of water molecules in a puddle of water. Research has shown that it can be challenging for pupils (and students) to move between and connect what you can see and experience with the naked eye to a representation at a molecular level; for example, see [12]. That a six-year-old pupil could connect what cannot be seen (water molecules) with what can be discerned at a macroscopic level in everyday life (a puddle of water), and in this way express a more scientific reasoning about the phenomenon than before the lessons, illustrates what can happen and what is possible when teaching is based on a multimodal design.

However, a critical aspect when designing lessons is that the teachers need to reflect on which representations (and modes) to use and how to use them in the classroom in order to maximize the possibilities for pupils' meaning making [25]. In some instances, during the present study, the teacher's design for learning appeared to be based on her own perspective rather than on the children's perspective. One such example is when the teacher showed a photo of an umbrella and rain, with the label 'LIQUID WATER'. This way of representing the phenomenon appeared to make it challenging for the pupils to make the intended meaning. One possible reason for this can be that the written text did not align with the visual representation from a pupil's perspective. Another example is when the teacher showed a photo of a foggy forest, with the intention to represent gas. This is problematic from a chemistry perspective, since fog appears when water vapor (water in its gaseous form) condenses into the liquid phase. It also seemed to be confusing for some pupils since the teacher previously had used a picture of steam when representing the gas phase. Based on these results and previous research [26], we argue that teachers need to select and unpack the representations they use in ways that support pupils' meaning making with the representations.

4.2. The Creation of Digital Animations Increases Pupils' Participation and Meaning Making

In the activity where the pupils built molecular models, they built them individually, although they were grouped together with others. However, when the pupils created the digital animations, all of them worked together with the other group members. Thus, one aspect of the creation of the digital animations is that the pupils were given the opportunity to develop their collaboration skills, to practice taking turns, and also to learn from each other. Some conflicts arose during this process, but that was something that the pupils solved by themselves. Thus, this study supports previous findings [43] showing that learning activities where digital tools and digital resources are afforded often create a high level of engagement, in terms of negotiating, contributing, making suggestions, and making choices of what signs to use. Furthermore, signs of learning could be discerned in all groups during the pupils' collaborative creation of the animations. Therefore, the creation process itself appears to be an important part of a teacher's design for learning. This strengthens previous research implying that pupils' meaning making in science can be supported by letting them create their own representations [17,34–37].

Another critical aspect that needs to be highlighted is the necessity for teachers to support pupils in using digital tools independently. In this case, the functions of the application were important for the pupils to be able to manage, so that they could focus on creating the animation rather than on technical aspects of the tools. Therefore, we want to emphasize the importance of teachers reflecting on what prior digital knowledge the pupils have and which technical aspects they need to be introduced to before creating digital representations.

4.3. Meta-Reflection about Pupils' Representations as an Important Part of the Lesson Design

Generally, lessons end when pupils have made some kind of representations. Thus, not all teachers and pupils engage in meta-reflective activities [33]. But how and to what extent the pupils' disciplinary understanding were presented in the digital animations they created varied in the present study. Thus, based on the results presented in this paper, the secondary transformation unit emerges as a very important part of the lesson design in order for teachers to gain a deeper insight into how pupils experience a phenomenon. During the secondary transformation unit, several signs of learning were discerned, that would have remained undiscovered if only the final representations had been analyzed. To have group discussions during the second transformation unit becomes an opportunity for pupils to express their experience, and thus for other pupils to make meaning. One example of this is when one of the pupils expressed her understanding of the connection between the macroscopic level (feeling warmth) and the submicroscopic level (rapid movement of water molecules) when she was given the opportunity to hold the stuffed animal Affe during a meta-reflective discussion. Another example is when the pupils represented water molecules in different states of aggregation through bodily action during the secondary transformation unit. Compared to the bodily action activity they participated in previously in the primary transformation unit, the pupils were more active and engaged during the same activity in the secondary transformation unit, and they did not need the teacher's support this time.

The results from analyzing the meta-reflections with the pupils shows that it is valuable to discuss pupils' representations with them, whether they are animations, drawings, or any other form of representation. Furthermore, to use a stuffed animal in the secondary transformation cycle appears to invite the pupils to ask questions "through" the stuffed animal, for example, if water molecules have eyes or a mouth, a question that was not asked during the lessons. A possible interpretation is that the stuffed animal helped some pupils to feel more confident in asking questions that they might otherwise not have posed. Thus, in order for teachers to facilitate for pupils to express their meaning making, it is important for teachers to reflect on how to design the secondary transformation cycle in their design for learning.

5. Conclusions

In this study, we have shown what can happen and what is possible when six-year-old pupils participate in multimodally designed learning activities where the pupils are given opportunities to both create their own digital representations and reflect upon them. We conclude that multimodally designed lessons can increase pupils' meaning making in chemistry, that the creation of digital animations can both increase pupils' participation and support their meaning making. Furthermore, we draw the conclusion that meta-reflection of pupils' representations can be an important part of the lesson design. We argue in line with Selander and Kress [33] that it is essential to take into account that when pupils are offered several ways to represent their knowledge, it also opens up for a broader assessment repertoire, where not only the written word or the spoken language should be acknowledged, but also that other forms of representation are recognized as signs of learning. A central aspect in the design of this study was that young pupils were given the opportunity to create digital animations to represent their meaning making and above all to talk about and reflect on their animations. Thus, we claim that it is of central importance for teachers to let pupils discuss and reflect on their process to create the digital animations and not only assess the final product. However, we suggest that this design can be further explored, for instance in other areas of science and with pupils and students of different ages. This type of research could strengthen the results in this study since there is a limited number of participants, which makes it difficult to draw general conclusions. Another aspect that would be interesting to explore is how and to what extent the pupils apply their experiences from these lessons in other related areas of science in the future. This can also be seen as a limitation of this study since the meta-reflective discussions took place during

the second lesson and the day after the second lesson. That is, we cannot say anything about how the pupils will link their experiences from these lessons in the future.

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