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Developing and Integrating an Augmented Reality App for Teaching and Learning About Enzymes

Wouter van Joolingen, Sui Lin Goei, Henri Matimba, Ryan Kyaw Thu Aung Ba, and Teresa Pedro Gomez Dias

Abstract In this chapter, we report on the development of an augmented reality (AR) app for teaching the working of enzymes. The aim of the study presented was to investigate how teachers and developers can work together in creating technology for education, in this case AR for teaching biology. In the project, four teachers from two secondary schools participated in a Lesson Study (LS) team with educators and developers of teacher training institutes and a professionals specializing in creating applications for virtual and augmented reality. We report on the process of development, the resulting app and lessons as well as on the first experiences in the classroom. The main conclusion on the process concerns the integration between lesson design and app development. Basic preparations on acquainting teachers with the use of AR and its content need to be made before starting the design and development cycle. Regarding the app itself, we identified improvements on the way AR can be a more integrated part of the learning activities.

Keywords Augmented reality · Inquiry-based learning · Lesson Study · Enzymes · Biology education

W. van Joolingen (✉) · H. Matimba
Freudenthal Institute, Utrecht University, Utrecht, The Netherlands
e-mail: w.r.vanjoolingen@uu.nl

S. L. Goei
LEARN! Learning Sciences, VU Amsterdam, Amsterdam, The Netherlands

S. L. Goei · T. Pedro Gomez Dias
Department of Human Movement and Education, Windesheim University of Applied Sciences, Zwolle, The Netherlands

R. K. T. A. Ba
Nanyang Technological University, Singapore, Singapore

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1 Introduction

Creating technology-based environments that allow students to experience environments that they can explore and play around with have been built and studied over at least the last four decades [4, 24]. Examples are the experiences where a learner or student is fully immersed in a computer-generated virtual environment [3, 27], but also through the use of simulations whereby physical properties can be explained and taught [5, 16, 17, 22]. The technology can also be used in helping a learner train practical skills and so reduce hazardous situations or to make the training program more cost effective [23]. In short, through the coexistence of virtual and real environments, learners can experience phenomena that would otherwise be unattainable in the real world.

In this chapter, we focus on a study on the use of augmented reality in biology education for upper secondary school. As a science, biology stands out as complex. It studies life, in itself a very complex object of study, it also studies life at many levels, from molecular processes within the cell to complete ecosystems. As a result, biological science operates at many levels, and it is important to investigate the relations between levels. For instance, the processes on the level of individual organism (e.g., taking in food) may lead to emerging phenomena (e.g., food shortage) on the population level. This process can, on the other hand, be caused by processes on a smaller level of aggregation, (e.g., low blood sugar levels leading to hormone production that causes an urge to eat). In order to fully understand biological processes and systems, it is therefore required that reasoning takes place on different levels of aggregation and between these levels. Such reasoning is called, with an interesting visual analogy, *yoyo-ing* [13]. Yoyo-ing requires awareness of the existing structure of biological levels of aggregation as well as knowledge of the links between these levels.

Yoyo-ing is an important part of *systems thinking* [10–12, 25], which is an approach that applies generic system concepts such as systems' boundaries, their hierarchical structure, their components and relation between them to biological systems at all levels. Systems' thinking implies a systematic way of approaching a biological system, accounting for all aspects of studied biological phenomena.

Systems' thinking relies to a large extent on *models*. Models are used as a means to mediate between a person's ability to understand complexity and the original system [15, 18]. As an example, a scale model of a torso with organs can serve to deal with the complexity of the human body and the way organs are positioned and connected. The torso allows to inspect the relative position of the organs, see the way they are connected by blood vessels but at the same time the torso leaves out much detail that may be unnecessary for the purpose of the model. In such a way, the torso helps students and teachers to reduce complexity and focus on the relevant detail of a biological process.

Combining systems' thinking and models implies that models can exist on multiple levels of organization. For instance, based on the torso model, if we are interested in the workings of one specific organ, e.g., the stomach, we need a model that will reveal more detail of the stomach and the processes that take place within [2].

Augmented and virtual reality are very suitable applications for providing models at these multiple levels. Augmented reality allows to add information to the observed reality, e.g., labeling body parts or visualizing the inside of the body. Virtual reality can help to zoom in or out between layers, e.g., from the organism level, to the organ level all the way down to the level of molecular processes in the organs.

The purpose of the current study was to explore the potential of AVR in biology education by focusing on the use of AR to allow students to travel through the several layers involved in understanding digestion. The main focus was on the digestion of carbohydrates, in particular, sugars and starch, in chemical terms mono-, di- and polysaccharides. In the digestive system, the longer chains of saccharides are broken down by enzymes into smaller chains and eventually glucose molecules, which can be admitted to the bloodstream.

We developed and evaluated an instructional app that was built to test the advantage of learning about the concept of enzyme operation, for the context of carbohydrate digestion, with the aid of a handheld device. The idea behind the choice is that for the learning of the concepts involved, students would be able to mentally visualize the conceptual ideas concerning the learning objective. We chose for handheld devices (i.e., android phones and tablets) because this does not necessitate the use of systems where the user has to be fully immersed in the learning environment and that students can use the learning tool (app) in conjunction with more traditional learning methods. The latter gives the opportunity to cross reference learning effects with or without the aid of additional AR learning tools. Furthermore, it is interesting to test to what extent is it possible to incorporate deep mental learning or model thinking in a task using AR capabilities. The latter is one of the key objectives of twenty-first-century skills and learning [26].

1.1 Using a Lesson Study Approach to Design, Develop and Test Instructional Learning Tools

A major decision in the development of the app was that its development process was integrated with the design of the lesson in which it was planned to use. This means that the development of the lesson planned informed the development of the app. At least in theory, then the app could be tailored to the demands imposed by the lesson design and reversely, the lesson can be based on the possibilities the app offers.

In designing the lesson, we followed the approach of *Lesson Study* (LS) [6, 9, 14]. In this approach, a small team of teachers designs a *research lesson* around a research question. The lesson design is primarily focused on understanding and predicting student learning processes in response to the interventions in the lesson. Once a lesson is designed, it will be performed live by one of the team members where the other team members will observe student learning. In the Dutch model of LS, the focus of observation is on selected *case students* for whom detailed predictions will be made as part of the lesson plan, following the model of LS introduced by Dudley [8] and De Vries and colleagues [6]. After teaching and observing the lesson, it will be revised and taught a second time. In a reflection stage, the LS team will use the data collected from the whole cycle and potentially move on to a new or updated research question after which the cycle can repeat. Figure 1 displays the full LS cycle based on its representation by Stepanek and colleagues [19].

Designing research lessons entails knowledge about the learner, as well as the subject or topic that is being instructed and available teaching methods and approaches. A strong emphasis is made in understanding what the student needs to be able to learn or fulfill the learning task. In order to obtain this goal, the teacher scrutinizes his/her action in a team of peers concerning a chosen lesson or part of thereof.

In the current case, the development of the app was integrated within the Lesson Study cycle. This means that in early meetings, the team developed ideas for the app that were taken up by the developer. In principle, subsequent versions of the app should be discussed in various team meetings. We were interested in the way the LS process would interact with the design of the AR application, the way the app would be integrated in a lesson and how students would use the app to support

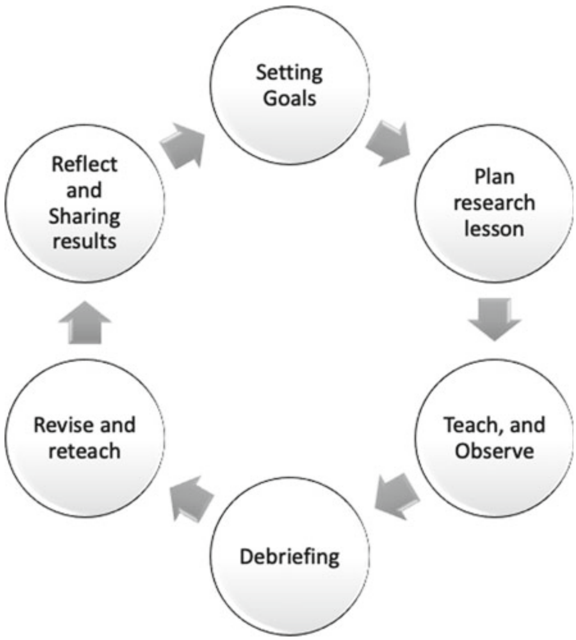


Fig. 1 Lesson Study cycle ref or based on the work by Stepanek and colleagues [19]

their learning. In the following, we describe the design phase of the app and the lesson as well as observations made in the lessons that were actually performed.

2 The Design Phase

2.1 The Lesson Study Team and the Design Team

The LS team consisted of four teachers of biology from two participating secondary schools, one LS expert who served as process facilitator, one teacher educator in chemistry, one teacher educator in biology and one researcher in science education who served as knowledgeable other with respect to modeling and ICT in education. The teachers had no or little experience with LS or with AVR. The team met several times over a period of a year to discuss the contents of the app, develop the actual lesson design, perform, observe the lesson and reflect on the process.

Next to the LS team, a smaller design team was set up, consisting of the teacher educator in chemistry and the researcher in science education, together with the app developer. This team was separate for two reasons. First, it was considered to be fruitful to separate the more technical talk from the talk on the lesson design. And second, the geographical separation (LS team in the Netherlands, developer in Singapore) made meetings with the full group hard to organize.

2.2 Choice for Target Group

In an early stage of the project, the team discussed the target group for the application. As the teachers in the group taught in different grades, it was decided to create an app that would be suitable for the use in both lower (grade 9) and upper (grade 11) secondary classes. This means that the app has to be functional for learners at the start of the learning about the domain, but also still be appealing to older students that have already acquired general knowledge concerning concepts such as enzymes and reaction conditions. This choice also implied that the app is not seen as a unit of learning in itself, but that it should be integrated in supporting materials and lesson designs, adapted to different target groups.

2.3 Choice of a Model Enzymatic Reaction

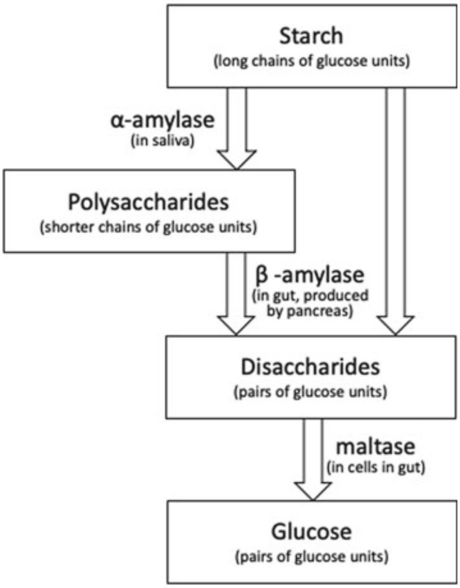
In the starting phase of this project, a choice had to be made by the participating secondary school teachers and university researchers which enzymatic reaction had to be chosen as the model reaction to be used in the app. Initially, the choice was made to build an app around theme of the occurrence lactose intolerance in humans. The occurrence of this intolerance is estimated to afflict about 65–75% of the global population [1], and it causes a condition characterized by symptoms such as stomach pain, bloating, gas and diarrhea, which are caused by lactose malabsorption. The rate of the occurrence also varies a great deal from region to region, from no more than 10% in Northern Europe to as much as 95% in some parts of Africa and Asia [7]. However, soon after the choice was made to build an app around the topic of lactose intolerance, it was abandoned, as it proved impossible to obtain the sought after structural chemical data needed to make an interesting and congruent scenario that could be used in the app. A major factor for this is the fact that the mechanistical considerations of the process are not yet fully understood in humans. After taking this into account, teachers and researchers decided to look for another model system.

This led first to the re-examination of the educational and methodological constraints governing the design of the scenario around the model system. A model system was sought that not only is specific toward a certain chemical process, but should also occur at different places in the human body, such as the muscles or the digestion system. This constraint narrows the choice of the possible model systems. It also gives rise to the opportunity to make allowances in the app to show the influence of vital secondary conditions, such as pH or temperature on the occurrence of the studied process.

The resulting model system chosen was the enzymatic reaction of the degradation of starch by amylase, following the description by Tomasik and Horton [20] as displayed in Fig. 2. This reaction plays an important and crucial role in the degradation of foods that contain starch, such as bread and potatoes. Starch consists of two types of molecules: One is a linear and helical chain (amylose), the other as a branched chain (amylopectin) build up from sugar units (saccharides). Plants and animals use these molecules to store energy. In our digestive system, starch is broken down into smaller fragments, called monosaccharides or glucose (1 unit), disaccharides (2 units) or polysaccharides (multiple units). This process occurs throughout different regions in the human digestive system. The process ultimately leads to the production of maltose (a disaccharide), which in turn is broken down to glucose in the intestines by the enzyme maltase. The enzyme that breaks down starch is called amylase, which occurs mainly in two variants, α- and β-amylase. α-amylase exists in saliva and can cut starch molecules in random places, resulting in polysaccharides of various lengths. β-amylase is produced in the pancreas and always splits off two glucose units at a time, resulting in maltose molecules. Important is that when swallowed, the α-amylase reaches the stomach and is *denaturized* meaning its molecular shape is unfolded due to stomach acids, and it loses its function.

Apart from starch also proteins, vitamins, cellulose, minerals and more substances are part of our diet. Within the context of this app, cellulose was decided to be particular interesting, as, just like starch, its molecules consist of chains or networks of glucose units, with as a difference that the way these units are bonded is

Fig. 2 Enzymatic conversion of starch [20]



different. As a result, amylase (or any other enzyme in the human digestive system) is not capable of digesting it, and it leaves the body undigested.

Taking these characteristics into account, the design team decided to create an app that focused on the digestive process of different kinds of food: bread, meat, fruit (a banana) and a soft drink. For each of the four items, the main components should be shown if where and how they would be digested by the two versions of amylase. These components could be starch and cellulose (bread), proteins (meat), fructose (a disaccharide) (banana) or maltose (soft drink). The app should allow students to choose one of these items and follow its digestion through a person's digestive system.

The app then could be used for several teaching goals as follows:

- To show the structure of the human digestive system
- To show that starch is digested (cut into smaller units)
- To let the student investigate the working of the two kinds of amylase
- To let the student explore three levels of biological organization (organism, organ and molecular) and move up and down between them.

An app that would provide views allowing for these tasks could be used both in lessons that support a first exploration of the digestive system, as well as a deeper understanding of the molecular processes that underlie the processing of starch in the body into glucose that can be dissolved in the bloodstream.

2.4 Building an Augmented Reality Application and a Lesson Plan Within a LS Cycle

The original idea was that the app would be designed in a separate design cycle, connected to the Lesson Study cycle, as depicted in Fig. 3. In the LS cycle, teachers would formulate their lesson plans and the resulting requirements for the app. Then in the secondary design cycle, the developer, together with the two experts who also participated in the LS team, versions of the app would be created for review by the LS team.

In practice, this proved to work differently, due to the different timescales of the two cycles. Developing the needed graphics took longer than expected, and therefore, the LS cycle was more or less halted for a relatively long time. Despite this drawback, interaction between the two development cycles took place on two crucial issues.

The first of these was the selection of the enzymatic reaction, as described in the previous section. The LS team at first chose for a different enzyme (lactase) to be the focus of the app, but it actually appeared from the first attempts to model this reaction in the app that it would be impossible to visualize. This initiated an exchange between the two cycles and the search for a better example enzyme reaction, resulting in the latter choice.

The second major decision that was made based on the interaction between the LS team was on the way the visualization would be integrated into the lesson. Here the lesson design steered the app development, in the sense that the scenarios were

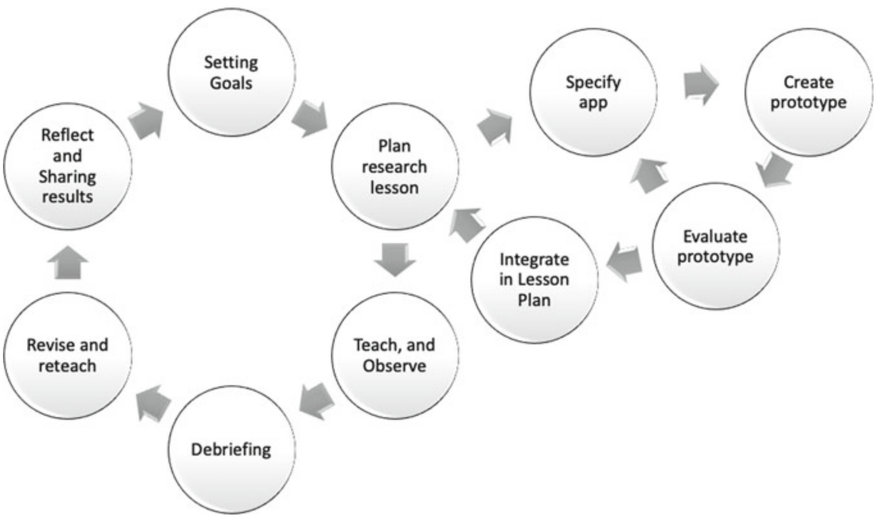


Fig. 3 Design cycle as an addition to the LS cycle

designed in the team, as part of the way the team foresaw students to explore the working of the enzymes, crossing the various levels of biological aggregation.

In the construction of the app, simple storylines were chosen all following the same principle. The learner starts at the macroscopic level, where a food is digested and subsequently followed as it takes its course through the human body. There are foods that contain starch, fibers, protein or a combination starch and fibers. After the digestion, the app takes the learner a level lower to the microscopic level of the molecules present in the food. It is possible to induce specific cleavage patterns by the enzymes (α- and β-amylase) when starch is present. This is governed by the position and type of enzyme in the body, so in the mouth you will only find the enzyme α-amylase and after the pancreas the enzyme β-amylase.

As a result, the app started from scanning a picture of a woman standing behind a table filled with food items (see Fig. 4). The app provides an overlay over the picture of a skeleton showing the relevant organs of the digestive system. Student can then pick a food item which takes them to a screen displaying the major organs of the digestive system: mouth, stomach, gut and bowel. Students can zoom in further on these organs and inspect the stage of digestion in that organ: α-amylase cutting up the starch in the mouth, its denaturation in the stomach, β-amylase chipping off disaccharides in the gut and the resulting glucose entering the bloodstream in the gut and the bowel. Moreover, depending on the food chosen, the presence of starch and other components of the food taken in are shown as well as the effect the both versions of amylase have on them (or not).

Lessons were designed for two levels of secondary education. For the 11th grade (age 16–17), who, in earlier lessons were taught the basic working of enzymes as well as the basic component, the students were to start with group work to investigate the working of the two types of amylase *before* interacting with the app. For this, they could use a reference book for the sciences to study their molecular structure and their working. Also, they used a depiction of the human digestive channel to label its components, as a reminder of the structure of the digestive system and to locate the place where the various stages of digestion take place. After this, they were asked to check the digestive path of starch, fibers and proteins using the app and to collect the results in a table, matching food components to enzymes and organs. The table was then made subject in a class-wide discussion, in which the teacher filled in the table, based on contributions by the separate groups.

In the design for ninth grade (age 14–15) classes, the app was used in a more explorative manner. The same table as for the 11th grade was used, but students were instructed to use the app from the beginning to investigate in which organs the enzymes operated. They used the information in the app to fill in the same table as was used for the 11th graders, and also this table was discussed with the whole class. This discussion was followed by an explanation by the teacher on how enzymes work, using a large display of the molecular structure of amylase.

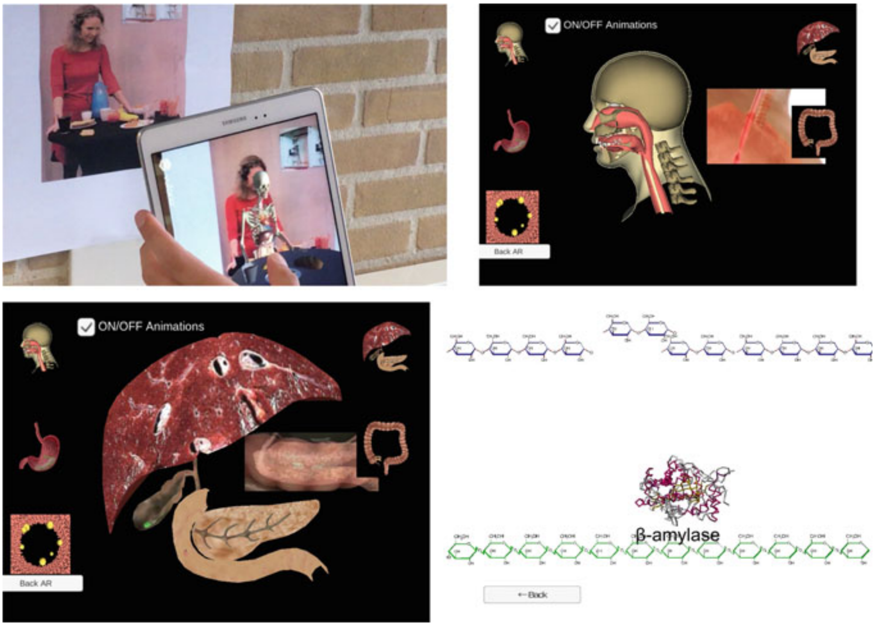


Fig. 4 Four screenshots of the app. The top left picture shows the app while the trigger picture is being scanned on the macroscopic level. Pictures in top right and bottom left show two aspects of the organ level (mouth and gut, with associated organs). The bottom right picture shows the molecular level and allows the student to use the amylase to cut the starch chain on top, but not the cellulose (fiber) chain on the bottom

2.5 The Lessons

The lessons were deployed as planned, once in a secondary school in the east of the Netherlands, where one of the teachers of the LS team performed the lesson for 11th grade and two times in a 9th grade class in the center of the Netherlands. In each class, three *case students* were selected who were observed by members of the LS team, and all research lessons were video recorded. Case students were also interviewed after the lesson. Students' active informed consent was gathered by their teachers, and in the case when students were underage, active informed consent of their parents was obtained.

In the 11th grade class, the lesson was performed as planned. Notably, students refrained from using the app until they completed their investigation in the specific enzymes and performed the learning tasks as instructed. After the investigation, students took the tablet and scanned the picture. Operation of the app proved no problem, after some experimenting, all students could operate the features of the interface. One of the case students enjoyed the "cutting operation", in which the enzyme can be used to cut the chains of starch into disaccharides.

One thing that was very clear in the lesson is that students typically used the app in a very systematic way: scan the picture, choose a food item and work systematically through the various organs to check whether amylase works on the substances that are present in the food. In the post-lesson interviews, case students stated that they liked the app and were satisfied with the lesson.

Also, in the ninth grade classes, the lesson went as planned. Here it became clear from students behavior as well as from the interviews with the case students that the students perceived the app as a game. One of the case students explicitly used this word in the way he described and analyzed the app. From this perspective, he critiqued the app on its game features and the way it could be improved.

3 Evaluation and Discussion

In this chapter, we described the development of an augmented reality app that provides insight into the working of amylase as part of the human digestive system. The app was designed in a collaboration between teachers and a design team, integrated in two lessons designs, which were tested within the classroom in three lessons. The cycle of design followed the LS approach, connected to the development team that implemented the app. The resulting lessons in which the app was employed were then performed and observed. In this section, we summarize the main findings from both the design phase and the performance of the lessons.

In the design phase, the initial intention was to integrate the design and development cycles, as in a rapid prototyping approaches [21]. The idea was that this would lead to a kind of agile development in which the LS team would be able to review subsequent versions of the app, decide on how these could be integrated in a lesson leading to more refined specifications. In practice, however, the process did not unfold as planned. Two factors seem important to this.

The first factor is that at the start of the cycle many decisions had to be taken which took a lot of investigation. For instance, although the plan was to focus on an enzyme, it took time to determine which enzyme was the most appropriate, both from an educational perspective and from a technical perspective. It was not helpful to this process that for the teachers this was the first time they were working with an AR environment, so they lacked experience and knowledge on its possibilities and limitations. As a consequence, it was hard to derive concrete guidelines for the app developer.

The second factor was that the developer was located in Singapore, while the team was in the Netherlands. Due to time differences and teaching schedules, a meeting of both teams together was impossible so two team members served as a liaison between teachers and developer. This indirect communication was probably not helpful for the speed of development. The resulting fact that the app development was slow relative to the LS cycle effectively stalled the LS cycle for a considerable time during which a version of the app was developed on partial specifications. Time constraints prevented that the design—evaluate—redesign cycle for the app could not be fully exploited after this time.

A lesson to be learnt from this is that it is important to prepare the LS and development cycle before they actually start. In the current case, this would mean that choices for an enzyme would need to be investigated and explored before the actual LS and development cycles would have started. Also, initial development of example displays, if only as a mock-up, could have boosted the creativity of the teachers for the lesson design. This would allow the team to use the basic material to discuss flows of the lesson, exploring the different ways the app could have been used in the lesson.

With respect to the app itself, the two lesson designs, albeit very similar to each other, showed that it was possible to use the app in both an explorative and confirmatory way. However, the way the students used the app showed that the paths they followed were quite linear: scan the picture, choose food and check the processes within the organs. While this did a good job in linking the various levels of aggregation visually, it left little room for active exploration. To this end, the app should be extended with more enzymes and food components so that students can explore all the combinations. The current version of the app also lacks a visualization of the actual process of enzyme docking, which would be helpful in understanding *why* a certain enzyme can break down a molecule.

The same linear way of working with the app also raises the question on how essential the augmented reality part is of the app design. In effect, the picture was only used to bring up the start screen of the sequence, where the user can choose a food item. In order to stress the relation with the macroscopic level, it could be considered to require the picture to stay in view and use animations to explicitly stress the movements between levels of biological aggregation. Then the AR aspect of the app could be more prominent and useful from an educational perspective.

Concluding we can state that the development process and the resulting app on enzymes provided valuable insights into the way teachers can be involved in the design of advanced technological tools in the classroom. While the process did not always turn out as planned, we can learn from the experience. The main lesson learnt is the importance of preparation, the availability of good examples and basic material is essential to get a proper development going in which teachers and developers collaborate in an effective way.

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