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Upper secondary students' thinking pathways in cell membrane biology – an evidence-based development and evaluation of learning activities using the Model of Educational Reconstruction

Leonie I. Johann [a], Fredrik K. H. Rusk [b], Michael J. Reiss [c] and Jorge Groß [d]

[a]Department of Teacher Education, Nord University, Bodø, Norway; [b]Åbo Akademi, Åbo, Faculty of Education and Welfare Studies, Finland; [c]Institute of Education, University College London, London, UK; [d]Department of Science Education, Otto-Friedrich-University of Bamberg, Bamberg, Germany

ABSTRACT

This study reports on the theoretical- and empirical-based design and evaluation of cell membrane biology learning activities within the Model of Educational Reconstruction and experiential realism. First, we designed analogy-based learning activities by considering students' and scientists' conceptions as described in the literature. Secondly, we carried out two video-taped teaching experiments to study students' learning processes when interacting with the learning activities. Interpreting students' conceptual development as thinking pathways enabled us to identify and understand the roots of their learning difficulties. Due to inherent ontological and epistemological presumptions, the students had difficulties in understanding that cell membrane structure determines their two-fold function: to separate and to connect environments in order to maintain living processes. The multiple analogies we employed helped foster conceptual development because they highlighted aspects of the concrete everyday experiences the students already had, but had not thought about. As a result of the learning activities, the students revised their conceptions regarding the terms *barrier, gatekeeper* and *environment* and connected these to a more coherent conceptual structure of cell membrane biology. Methods and outcomes of the study may contribute to a better understanding of how this important concept can be brought to science classrooms.

KEYWORDS

Model of Educational Reconstruction; experiential realism; students' conceptions; learning processes; cell membrane biology

Introduction

Understanding cell membrane biology (CMB) is important because it provides insights into the underlying mechanisms of multicellular (mal-)functioning (Watson 2015). Due to the growing importance of this field for the general public, understanding concepts in the domain of molecular life science is not only critical for scientists, but also citizens (Duncan and Reiser, 2007; Tibell and Rundgren 2010) to make informed decisions and take part in scientific discussions – as illustrated by the ongoing COVID-19 pandemic.

As described below, the data in this study were gathered in Norway. In the latest Norwegian curriculum, revisions for upper secondary schools (Utdanningsdirektoratet 2021), both *biology in society* and *biological processes* are emphasised as core ideas of modern biology education. The latter includes knowledge regarding the relationships between cellular structures and functions, such as intercellular communication facilitated by cell membranes.

CONTACT Leonie I. Johann leonie.johann@nord.no

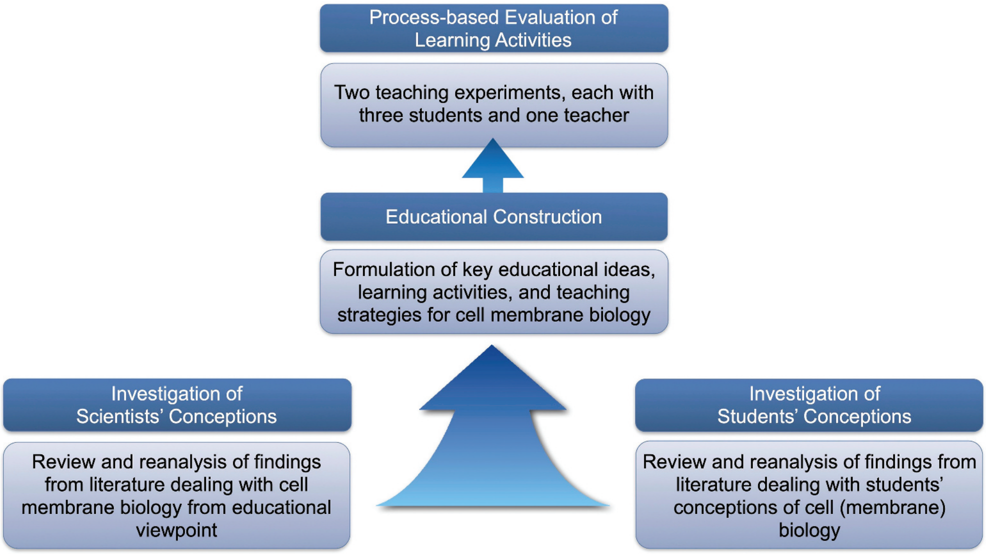


Figure 1. Design of the study according to the Model of Educational Reconstruction.

We see learning as a process where individuals in social discourse develop existing conceptions (Vosniadou 2014); students' conceptions therefore need to be considered in the design *and* evaluation of learning activities (Duit et al. 2012). Existing studies examining CMB for the purpose of education seem, however, either to take for granted existing science content (Gregers and Suhr Lunde 2021; Rundgren and Tibell 2010) or to examine learning only as outcomes from teaching (Marek, Cowan, and Cavallo 1994; Sanger, Brecheisen, and Hynek 2001).

Regarding these considerations, this study aims to make CMB more accessible for upper secondary teaching and learning. To achieve this, we employed the Model of Educational Reconstruction (MER) (Duit et al. 2012), and experiential realism (Gropengießer 2003; 2007; Lakoff and Johnson 1980) in our conceptual framework. Combining the MER's moderate constructivist epistemology (Duit 1996) with ideas from cognitive linguistics has previously proven a powerful approach to link the development of student-orientated learning activities to their evaluation (e.g. Kersting et al. 2018; Messig and Groß 2018; Riemeier and Gropengießer 2008).

In this study we drew on the three components of the MER (Figure 1): the investigation of (1) scientists' and (2) students' conceptions by means of reanalysing existing literature, and (3) educational construction to design learning activities. Subsequently, we empirically studied the impact of the learning activities on students' conceptions in two teaching experiments (Komorek and Duit 2004).

The research questions guiding our study were:

(1) How can students' and scientists' conceptions as described in the literature be used to design learning activities for CMB?
(2) What characterises students' conceptions while interacting with the designed learning activities?
(3) What implications for CMB teaching and learning can be drawn from (1) and (2)?

Conceptual framework

Drawing on moderate constructivist ideas, we consider students' conceptions as basic prerequisites rather than obstacles for learning (Duit 1996; Vosniadou 2014). According to the perspective of experiential realism (Gropengießer 2003; 2007; Lakoff and Johnson 1980), conceptions are mental models which are grounded in recurring social and bodily experiences become embodied as part of people's intuitions. In that way, conceptions become viable tools to interpret the world in which people live.

Furthermore, we hold the view that thought is imaginative. This means that for concepts which we cannot directly experience (as is the case for most scientific concepts, and also for feelings), we draw on our concrete experiences as source domains to construct understanding of the abstract target (Lakoff and Johnson 1980). To do this, we employ, amongst other tactics, metaphors and analogies. The latter highlight similarities between concrete source and abstract target domains; however, while analogies make explicit the comparison of structures of two domains (e.g. life is *like* a race), a metaphor (e.g. love is a burning flame) does not: 'Metaphors always have some aspect of surprise; they provoke anomaly' (Duit 1991, 651). In that sense, we understand as analogy everything that explicitly involves comparisons (which also involves examples) (Duit 1991), whether that is through linguistic expression or other modes of representation (such as visual depictions) (Tang, Delgado, and Moje 2014).

Science educators have in recent decades increasingly employed the ideas of cognitive linguistics to analyse students' and scientists' language in order to shed light on the underlying, often implicit source domains to understand potential roots for misunderstandings (Kersting et al. 2018; Messig and Groß 2018; Niebert and Gropengießer 2014). Since students and scientists are embedded in specific networks of common experiences in their day-to-day living, they may hold dissimilar conceptions, even though these are based on a common language. Hence, what is meaningful to scientists is often not to students and vice versa (Leach and Scott 2002).

In this paper, we examine students' and scientists' language by means of focussing on terms (e.g. *barrier*), and concepts (composed of several terms in relation to each other) that students and scientists use when explaining CMB. Concepts get expressed partly through linguistic expressions (e.g. 'cell membranes are barriers'), but also via other modalities, such as diagrams, depictions and models (e.g. the fluid mosaic model) (Gropengießer 2003).

State of research into students' conceptions of cell (membrane) biology

In line with these considerations, it appears that most student learning difficulties regarding cell biological concepts are rooted in how they construct understanding in the light of their concrete experiences.

Several studies that have investigated students' conceptions of cell biological concepts[1] (Flores, Tovar, and Gallegos 2003; Garvin-Doxas and Klymkowsky 2008; Lewis and Kattmann 2004) suggest that differences between the understandings of scientists and students often seem not only rooted at the level of individual conceptions (such as different understandings of the concept of *division*), but also result from differing ontological and epistemological presumptions. While cell biologists seem to understand biological functions in terms of their underlying mechanisms and processes (Johann et al. 2020; Trujillo, Anderson, and Pelaez 2015), students appear to reason teleologically, thinking that structures and processes exist for the purpose of function and are therefore highly efficient (Lewis and Kattmann 2004; Trommler and Hammann 2020). Students therefore have difficulties understanding how biological functions relate to underlying chemical structures (Garvin-Doxas and Klymkowsky 2008; Lewis and Kattmann 2004) and how the different levels of biological organisation (such as the molecular, cellular, tissue and organismic level) relate to each other (Knippels and Waarlo 2018).

State of research into strategies to foster learning in cell biology

To foster learning of cell biological concepts, it has proven fruitful to offer students suitable new experiences to illustrate new aspects of the experiences students already have. For this purpose, learning with multiple analogies has been shown to be a powerful learning strategy. As an example, to foster students' learning of *cell division*, Riemeier and Gropengießer (2008) let students break a chocolate bar in order to enrich their existing everyday experience of *division* as 'becoming more'. Observing that chocolate breaks into more and *smaller* pieces was apparently a meaningful analogy to the students which enabled them subsequently to construct the understanding that cell division must be followed by a process of cell growth.

Riemeier and Gropengießer (2008) stress, however, in line with other science educators (cf., Duit 1991; Kersting et al. 2018; Venville and Treagust 1998), the pitfalls of learning through analogies: namely, when the source domain is inadequate to understand the target, and when the analogy is too abstract for students to understand. The latter can lead to students refuting rather than accepting the new experience because they experience too great a cognitive conflict (Hewson and Hewson 1984; Vosniadou 2014). The need to combine multiple analogies for the purpose of learning has therefore been emphasised since a single analogy alone cannot provide all necessary aspects of a source domain. Similarly, it has been argued that not only the combination of analogies but also the use of multiple modalities (such as text, diagrams, etc.) can promote learning in science (Tang, Delgado, and Moje 2014).

Methods and design

In the following, we report on the production and analysis of data within the three MER components. First, we report on the process of constructing key educational ideas and learning activities for CMB, before we report on the empirical evaluation of the learning activities in two teaching experiments.

Educational construction of key ideas and learning activities for cell membrane biology

Selection of literature

To identify and understand students' conceptions of CMB, we examined and reanalysed literature on upper and lower secondary students' conceptions of this concept. The literature mainly concerns diffusion and osmosis (the most extensively researched conceptions in relation to cell membranes) and the molecular structure and function of cells and cell membranes. We therefore examined studies documenting students' conceptions before (Garvin-Doxas and Klymkowsky 2008; Rundgren, Chang Rundgren, and Schönborn 2010), during (Rundgren, Chang Rundgren, and Schönborn 2010; Verhoeff, Waarlo, and Boersma 2008) and after teaching (Dreyfus and Jungwirth 1988, 1989; Flores, Tovar, and Gallegos 2003; Franke and Bogner 2011; Gregers and Suhr Lunde 2021; Marek, Cowan, and Cavallo 1994), along with reviews of these studies (Hasni, Roy, and Dumais 2016; Riemeier 2005).

To identify and understand scientists' conceptions of CMB, we explored and reanalysed studies examining CMB content from an educational point of view (Johann et al. 2020; Mil et al. 2016; Rundgren and Tibell 2010; Trujillo, Anderson, and Pelaez 2015).

Analysis of literature

The reanalysis was mainly based on metaphor analysis (Lancor 2014; Moser 2000; Schmitt 2017), informed by the ideas of experiential realism (Gropengießer 2003; Lakoff and Johnson 1980;. That means we systematically screened the literature for original utterances by students and scientists, before we identified metaphorical constructs (such as metaphors, analogies, examples and models) and then reconstructed metaphorical models. We screened the selected texts for, amongst other grammatical terms, verbs and their cases, in order to look for phrases and terminology which could be understood beyond their literal meaning (source area) and transferred to a target domain (Lakoff and Johnson 1980; Schmitt 2017). In the course of this, we consulted an anglophone online dictionary (Lexico n.d.) to decrease our own possible blindness towards terminology that we, as scientists, might not immediately recognise as metaphorical. Meanings and possible source and target domains were discussed in-depth within the author team.

Elaboration of key ideas and design of learning activities

Our findings indicate that students often hold conceptions which are inadequate for the scientific understanding of cell membranes, even though they draw on similar source domains as do scientists. These source domains are:

- barriers and their separating feature,
- gatekeepers and their discriminating feature,
- the environment and its surrounding feature.

It appears that due to different ontological and epistemological presumptions, students and scientists draw on different aspects of these source domains (Figure 2) and consequently associate different meanings to terms. When students speak of cell membranes as barriers, they appear to have in mind a *one-dimensional* dividing line which surrounds each cell and separates cells by means of keeping all cells' components (mainly the nucleus) inside. The existing literature refers to students having a 'fried-egg' or 'brick' model of the cell (Clément 2007; Dreyfus and Jungwirth 1988).

Scientists, on the other hand, appear to draw on the fluid-mosaic model (Figure 4) for their understanding of CMB. They have in mind *three-dimensional* barriers which, because of their unique molecular make-up, came in the course of evolution to separate insides (water and substances, some crucial for life) and outsides (water and substances) from each other to shape cells *and* organelles (leading to distinct environments that can carry out distinctive biochemical reactions). Thus, scientists have in mind environments as the conditions in which cells thrive and

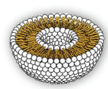
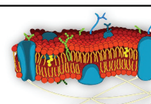
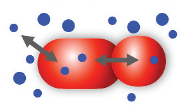
Central Terms used by Scientists and Students	Student Conception	Meaning	Scientific Conception	Meaning
Barrier	outside | inside **Cell membrane as a single line**	isolation into a single cell ('brick' model)	 **Cell membrane as spherical bilayer**	isolation into multiple cells based on lipid bilayer
Gatekeeper	 **Cell membrane as a gatekeeper that makes decisions**	purposeful selection to guarantee that only needed substances enter and waste leaves ('human nutrition' model)	 **Cell membrane as a functional layer**	embedded proteins with different functional tasks in the layer that arose during evolution
Environment	 **Cell membrane as a surrounding barrier**	static line that separates the cell from the dangerous environment ('fried egg' model)	 **Cell membrane as a communicating layer**	dynamic connection between inside and outside ('fluid-mosaic' model)

Figure 2. A comparison of students' and scientists' conceptions of terms which both groups see as key to understanding cell membrane biology.

Table 1. Relationships between the key educational ideas, critical terms to understand CMB and learning goals.

Step-by-step connection between terms to construct concept	Key educational ideas	Learning goals
Barrier ↕ Gatekeeper ↕ Environment	• Cells membranes (CM) separate cells (or membrane-bound organelles) into individual compartments which each contribute to the function of the cell/tissue by carrying out different tasks. • CM have a unique molecular make-up. Lipids determine the spherical shape of cells, thereby separating them in aquatic environments. • Cells are surrounded by water and/or other cells. • The lipid bilayer is a barrier for hydrophilic, big substances, but allows the continuous passage of small and hydrophobic substances. • Proteins are embedded in the lipid bilayer. They allow for the controlled passage of hydrophilic substances and enable communication with other cells. • Proteins are produced by the cell. Different cell types have different protein composition which changes in response to environmental stimuli.	• Understand CM as facilitators for separation (division) into individual rooms (cells, membrane-bound organelles) which make up to the same organism (cell). • Understand all membranes as analogous structures. • Understand that cell membranes are part of cells due to their molecular structure and that there would be no cells without cell membranes. • Understand that a cell membrane is a lipid bilayer with embedded proteins. • Understand that amphiphilic lipids as emulsifiers build a separating layer in water because they spontaneously assemble into a lipid bilayer. • Understand that only small or substances soluble in fat can pass the lipid bilayer. • Understand that proteins can have several functions: provide channels for substances soluble in water and facilitate communication with other cells. • Understand that proteins are produced by cells according to environmental stimuli and therefore are continuously changed.

communicate. As a consequence, they think of cell membranes as *gatekeepers* that maintain homoeostasis by enabling continuous exchange of substances *and* the regulation of other substances, such as ions involved in processes of energy transfer.

Students, though, often understand cell membranes in terms of decision-making gatekeepers that purposefully discriminate between needed and undesired, dangerous substances in order to protect cells and allow for their survival (much in the way humans intentionally discriminate in substances when they eat).

From this comparison, we conclude that a key educational idea must be that cell membranes allow life to exist (a focus on processes) and be maintained (a focus on molecular mechanisms) by means of both separating from and at the same time dynamically connecting with an environment (other cells and the external environment). In order for students to understand this key idea in terms of their own conceptions, we divided it into six ideas (Table 1)[2] and formulated corresponding learning goals which aimed at introducing the chemical features of amphiphilic lipids and membrane proteins step-by-step.

To set into action the key ideas, we designed multiple, mainly analogy-based, learning activities using different modalities (linguistic expressions, chemical structures, etc.) which aimed at highlighting new aspects of the terms *barrier, gatekeeper* and *environment*, which students seemed largely unaware of. Table 2 provides an overview of the learning activities, and the employed learning material, while Figures 3–9 illustrate each learning activity.

Table 2. The learning materials, the learning activities and explanations of the learning activities.

Learning material	Learning Activity	Explanation of learning activity
Concept cartoon (Figure 3)	1. The function of the cell membrane	Five characters discussing 'What is the function of the cell membrane?'. For the design of the statements, students' phraseology according to the literature was used.
Thought experiment	2. House analogy	Rooms in a house as an analogy to cells/organisms
Depictions of chemical structures (Figures 4, 5 and 6)	3. Illustrations of water and phospholipid molecules, fluid mosaic model and liposome structure	Relationships between individual molecules, their chemical features and the fluid mosaic model
Different coloured and shaped candies (Figures 7 and 8)	4. Candy analogy: candies as an analogy for amphiphilic lipids and proteins	Candies with different colours and shapes as analogies to lipids and proteins for students to understand that it is not the shape of these (head and tail) which determines their fundamental function, but their polarity (different colour of the candies)
Glass with water, fluid plant oil and table sugar (Figure 9)	5. Fat analogy: fat droplet in water as an analogy for cell in aqueous environments	When plant oil enters water, it assembles into fat droplets which should be recognised by students as analogous to micelles and cells
Glass with water and table sugar	6. Solubility analogy: behaviour of sugar in water and fat as an analogy for substance transport across cell membranes	Sugar dissolves in water. This should by recognised by students as analogous to the hydrophilic nature of membrane proteins.
Thought experiment	7. Everyday examples: drug addiction and COVID-19	Continuous intake of drugs such as caffeine leads to increased number or receptor proteins. For students to recognise relationship between phenotypic traits and molecular causes.

Evaluation of learning activities in teaching experiments

To study the impact of the learning activities on students' conceptions, we carried out two teaching experiments (Komorek and Duit 2004), in each case working with a group of three students and one teacher (the first author functioned as both teacher and researcher, while the second author assisted with the experiments).

Teaching experiments as an empirical method that allow for the combination of an intervention (teaching) with investigational aspects (interview situations and pre-and post-instructional questionnaires). As we conducted the teaching experiments we gained evidence regarding students' individual pre-instructional conceptions, and their collective thinking pathways. The role of the teacher was twofold: to identify students' conceptions by being an active dialogue partner and interviewer (mainly by asking open questions); and to offer learning activities depending on students' (developing) conceptions. The sequence of the learning activities therefore differed slightly in the two groups. The students were assured that the aim of the teaching was not to evaluate their answers, but gain insight into their thoughts.

In addition to increasing the trustworthiness of the results, the pre-instructional questionnaire aimed at increasing students' curiosity for the teaching to come. For this purpose, we designed four open questions according to the elaborated key educational ideas (e.g. 'What do you think is the function of cell membranes?') to invite students to articulate their beliefs. The language employed in the questionnaires, in the same way as during teaching, was mainly based on students' own rather than scientific terminology.

The teaching experiments were conducted in a seminar room at a local Norwegian University within walking distance of the upper secondary school that participating students were attending. They each lasted about 120 minutes and were videotaped to document non-verbal interactions, such as facial expressions and gestures, and help us understand facets of the students' collaborative discourse (Niebert and Gropengießer 2014).

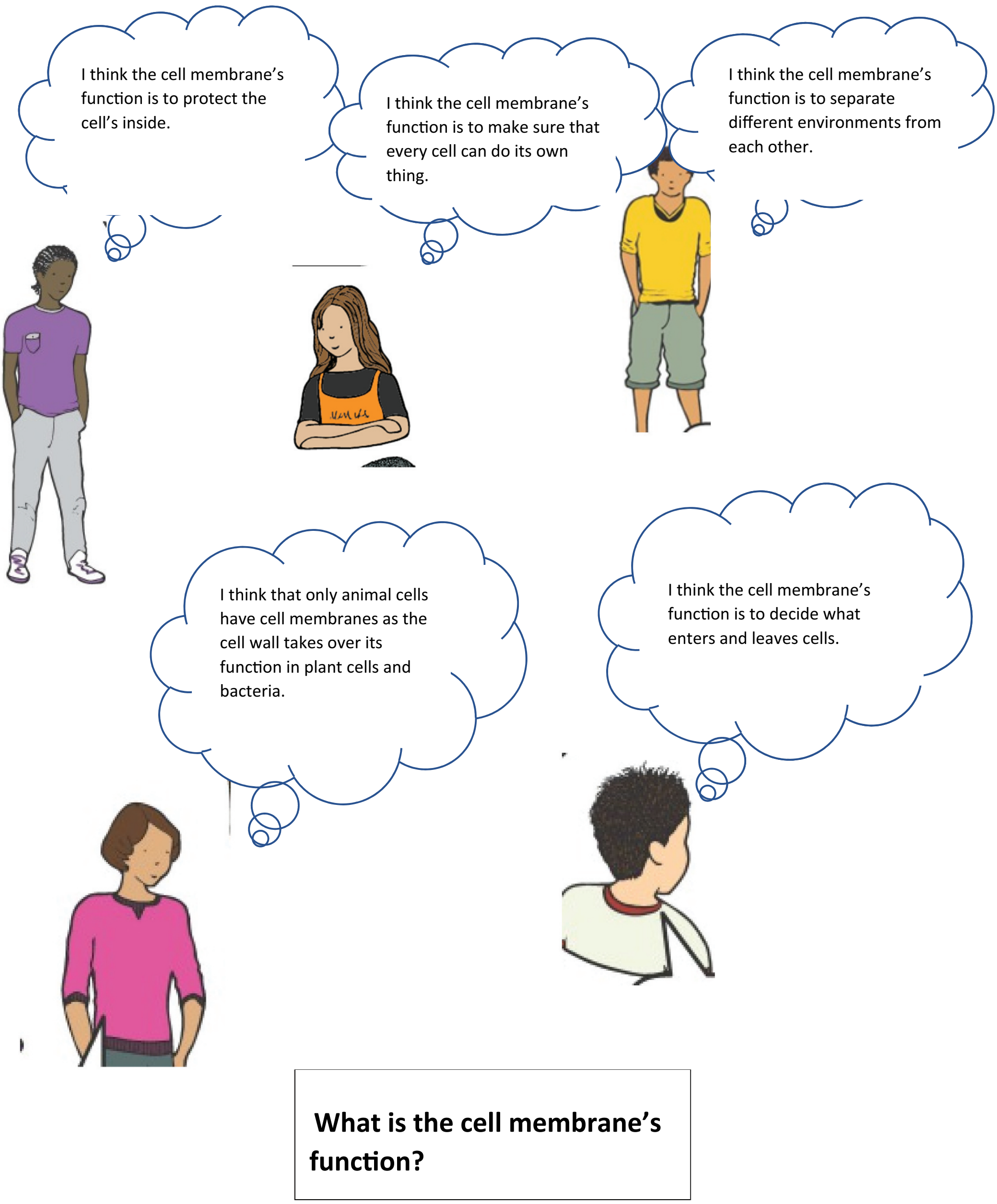


Figure 3. Concept cartoon to guide students' attention to the language they use.

Participant selection for teaching experiments

Regarding our aim to foster students' collaborative discourse, important criteria for participant selection were that the students had similar previous knowledge regarding CMB, were communicative and motivated, and knew each other in order to create a relaxed atmosphere. Therefore, we picked upper secondary students (in all, two girls and four boys) aged 18–19 who had completed at least one of the two biology courses which are offered at Norwegian upper secondary schools. The

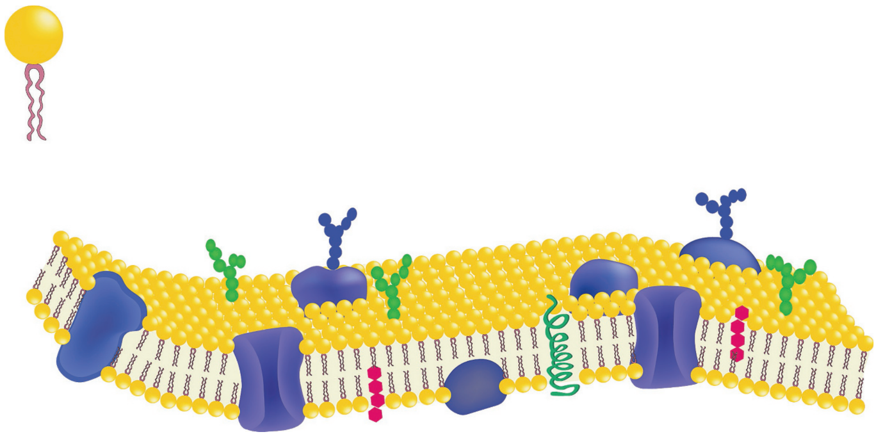


Figure 4. Relationship between amphiphilic lipids and the fluid mosaic model of cell membranes.

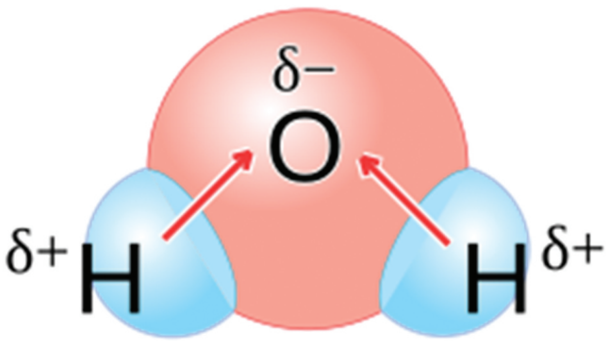


Figure 5. Chemical structure of water molecule to better illustrate the concept of polarity.

final selection decision of the composition of the student groups was taken by their classroom teachers according to the above selection criteria. To participate, all students provided provided informed, written consent.

The teaching experiments took place at the beginning of the spring 2020 outbreak of COVID-19. At that time, the teaching situation at high schools in Norway was rather unclear, which was challenging for both teachers and students.

Analysis of teaching experiments

To translate and condense the video recordings into written text and subsequently identify, generalise and interpret students' conceptions, we conducted a stepped process guided by qualitative content analysis (Gropengießer 2005; Mayring, 2004) and cognitive-linguistic analysis (Lakoff and Johnson 1980; Moser 2000; Schmitt 2017):

- Processing: The transcription of spoken utterances from the video data into written statements (text) and the subsequent condensation of the text.
- Evaluation: The organisation of students' statements into categories (conceptions) by means of assembling similar statements according to content and experiential grounding. By means of explaining students' evolving conceptions through the results of cognitive-linguistics, we further developed the category system.

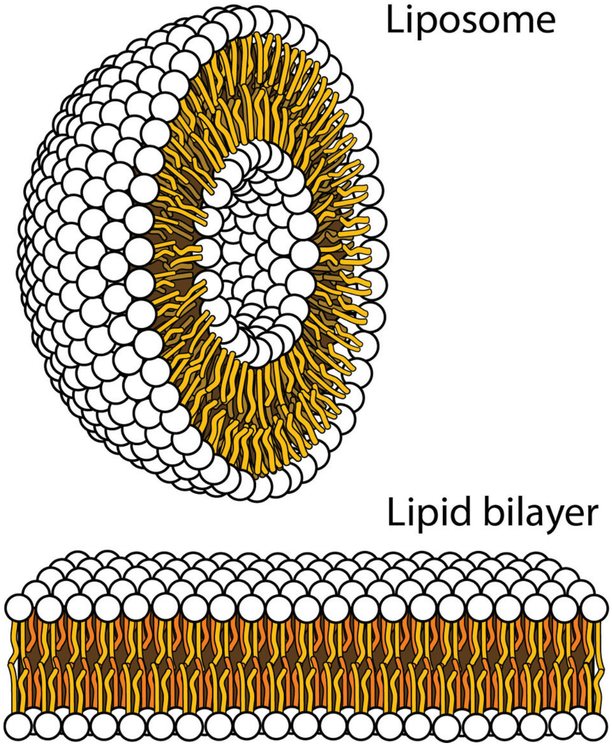


Figure 6. Liposome structure to help visualise that lipid bilayers form spherical cell-like structures.

Figure 7. Different types of candies as analogies for amphiphilic lipids and proteins for students to remodel the fluid mosaic model.

Figure 8. Prototype of candy cell membrane model.

Figure 9. Visualisation of a fat droplet in water as an analogy to a liposome.

- Structuring: The finalisation of the categorisation by aligning both groups of students' conceptions to each other.

The whole analytical process was discussed in-depth among the authors in order to minimise subjective mis-readings and opinions. After the analysis, all data cited in this article were carefully translated from Norwegian to English where the utmost attention was given to maintaining, so far as is possible in translation, the meanings of students' utterances, and the nature of their dialogues.

Results

In the following, we give, responding to our second research question, a step-a-step explication of students' identified thinking pathways as a means of indicating their developing conceptions while working with the learning activities. For this purpose, we show, for reasons of space, selected utterances and transcripts from *one* group (Jonathan, Hans and Konrad, all pseudonyms) which illustrate general characteristics typical of both groups.

Cell membranes surround cells and protect their insides from the outside environment by deciding what enters and leaves

Discussing the different statements of the characters in the concept cartoon, Hans, Jonathan and Konrad quickly agreed that the function of cell membranes is to protect cells 'from the outer environment' (Hans), to prevent 'chemicals and other things that are not supposed to come into cells' (Konrad) from entering. Students' rapid agreement about this was unsurprising, given that in the pre-instructional questionnaires they had all written statements which were almost identical to comparable ones in the concept cartoon. Therefore, initially the students found their conceptions confirmed and saw no need to query these.

Apparently, the students drew on two different everyday meanings when thinking of *protection*: either as an act to be carried out actively by 'somebody' (the cell membrane has human features) or as a passive state of being protected (the cell membrane has wall-like features). From the students' point of view, it therefore seemed reasonable that membranes are somewhat rigid (wall-like) and at the same time 'decide' (Jonathan) – a human feature – what 'enters and leaves cells'.

According to this understanding of cell membranes, the students were consequently unsure if plant cells have cell membranes (because they have cell walls). This uncertainty was also fostered by their experiences with school biology textbooks where plant cells look like 'rectangles', so 'you just see cell walls in between cells' (Hans).

Furthermore, the students appeared to think of *environments* as the natural world as opposed to the human world (Lexico n.d.). As humans tend to experience the environment as hostile, it made sense for the students that cells in the same way as humans *protect* themselves *from* potentially hazardous substances (so that only substances that are needed, such as nutrients, enter cells). According to their everyday experience that substances enter our body (a container-like object) through the mouth, students deduced that substances also enter cells at one 'specific point' in the cell membrane (Jonathan). In accordance with this point of view, the students initially did not find it plausible that cell membranes *separate* different environments from each other because separation for them meant physical restriction: in the same way as humans cannot be physically separated from nutrients, 'cells need oxygen'; therefore, cell membranes 'cannot keep oxygen outside' (Konrad).

Cell membranes separate both cells and organelles, thus contributing to increased organisation

In order for students to reconsider their conception of separation, the teacher requested the students to discuss one of the concept cartoon's statements they hitherto had paid little attention to: that membranes 'make sure that that every cell can do its own thing'. Surprisingly, this resulted in the students immediately constructing the analogy between a (eukaryotic) cell and its organelles: they remembered that (some) organelles, such as mitochondria, also have membranes which make such an organelle 'in principle its own cell' (Hans). When the teacher asked what the advantage of a cell in a cell might be, Konrad apparently recognised the plausibility of cell membranes having the feature 'to make sure that cells can make do their own thing' because 'it accounts for all types of cells'. Either way if they are cells in cells, 'all do their own things' (Konrad) and can therefore 'collaborate' (Hans). Since the students had apparently begun to reconsider their everyday concept of separation (as physical restriction), the teacher decided to introduce the *house analogy* as follows:

101 ***Teacher (T)***:	So let's think of it more abstractly. Like, we have a house. And the house has different rooms. And we have five children, and a mother, and a father. And then you have a house which does not have rooms. What advantage might arise with several rooms?
105 ***Konrad***:	It gets more **organised**[3] and you **separate** the different . . .[4]
106 ***Hans***:	. . . tasks that must be done.
107 ***Konrad***:	Yes. **You do not mix them**. So, you can see it in a cell too. We see the analogy to prokaryotes and eukaryotes. So, you have the five children, and the mother and father who each **have their rooms where they can do their own things**. But in a prokaryotic cell it is less organised.
111 ***Hans***:	So, in principle they make own rooms.
112 ***Konrad***:	In any case **compartments**.
113 ***T***:	So, what is a [eukaryotic] cell in principle?
114 ***Hans***:	A house with multiple rooms.

It seemed that the house analogy and the preliminary discussions were fruitful in terms of guiding the students to the anticipated learning goal. The evidence for this was that the students had started to provide mechanistic explanations by means of employing two new terms which refer to part-whole relationships: *compartments* refer to parts of a bigger whole while *organisation* refers to coordination or structuring of multiple parts (Lexico n.d.).

Cell membranes are built in a way that allow certain substances to enter and leave

To guide students' attention to the mechanisms for separation, the teacher picked up students' phraseology that cell membranes 'decide' what enters and leaves cells by asking: 'Isn't it like that we borrow the term "to decide" from the human world when we consciously decide something? How does that work in the cell?'. This led to the following discussion between Jonathan and Konrad:

201 ***Jonathan***:	Well, in any case they do not go about thinking if they want to have some water here or there.
203 ***Konrad***:	If something is supposed to leave the cell, it must be **edited** in a way that it is **naturally** allowed to come in. The cell membrane is there all the time. So, it is about which substance that comes to enter the cell.
206 ***Jonathan***:	Yes, like **it is built in a way** it always allows certain substances to enter.
207 ***Konrad***:	Mmm, so, if you want some substances out, it is not the cell membrane that **decides**, but the substance must **be made in a way** it is capable of leaving.
210 ***Jonathan***:	Yes, like it is made in a way it can always let certain substances pass, yes.

Jonathan's reaction to the teacher's questions illustrates that when directly confronted with his own phraseology, he experienced some unease. Consequently, he hastened to assure her of his awareness that the way he pictures cells to 'think' was meant metaphorically (lines 201–202). This unease appeared to result in Jonathan and Konrad recognising it as problematic that their explanation was insufficient to explain the mechanisms for substance passage through cell membranes, which triggered an urge to search for more plausible explanations (lines 203–206). In advance of the dialogue above, the students had remembered that there were 'ATPases' in cell membranes. Evidently, the question asked by the teacher fostered a connection to this previous knowledge because the students reasoned that structures somehow must determine functions (lines 206–210). Although the students' explanations were still shaped by a combination of anthropomorphic (the cell membrane 'allows' and the substance is 'capable') and teleological ('the substance must be made in a way', and comes in 'naturally') explanations, what was new was that they had further developed their mechanistic explanations (the cell membrane 'is built in a way' and substances are 'made in a way'). What apparently hampered students in realising the relationship between cell membrane structure and function seems to have been their difficulty in understanding the scientific meanings of terminology connected to cell membrane structure:

211 ***Hans***: If I remember correctly there is a hydrophobic and hydrophilic ...

212 ***Jonathan***: Yes, but are there just lipids on one side of the membrane and something else on the other? I don't know .[5] are not lipids hydrophobic or something?

214 ***Konrad***: Yes, I see what you mean with non-polar and ...

215 ***Hans***: Yes, but they have two ends, and the one is, for example, a lipid and then there is another one. I think that is phosphorus which is not fat-soluble or what it is.

It appeared that the students at this time of teaching remembered the shape of membrane lipids (see Figure 4) (a hydrophilic head and two hydrophobic fatty tails) which is usually referred to in Norwegian school books, but apparently not the meaning scientists give to this (the molecule is polar). Therefore, the students had difficulties imagining that cell membranes are made up of amphiphilic lipids because they appeared to misunderstand the relationship between lipids and cell membranes (line 212).

After this discussion, the teacher introduced learning activities 3 and 4 (see Table 2). At first, it seemed that these activities confused the students by provoking contradictory conceptions; they first became plausible in combination with learning activities 5 and 6. Initially, it seems that the students experienced too great a cognitive conflict with their ontological presumption that the lipid bilayer exists to enable protection and is not the result of the chemical features of amphiphilic lipids. They therefore had difficulties constructing an analogy between the different colours of the candies and the polarity of membrane lipids (instead, they constructed a more evident analogy between the shape of the candies and the shape of lipids in the fluid mosaic model: 'This was one looks like it has a head and a tail[6]' Jonathan). When the teacher asked if they could explain 'Why is it that there is a double and not a single layer of lipids?', the students therefore fell back on their anthropomorphic and teleological explanations: 'I am very sure it only works with two [layers] because cells chose to use two' (Jonathan).

Cells are natural bubbles embedded in water and cell membranes their natural, fatty barriers

Apparently, what helped students to solve their misunderstanding about the significance of chemistry for cell membrane structure was when they *observed* the behaviour of fat in water (learning activity 5), because this enabled them to understand that the lipids in a cell membrane are what they know as ‘fats’ from their everyday lives. This insight appeared to enable them to make sense of the information that cells are embedded in aqueous environments and that these influence their spherical structure. Evidence for the plausibility of the learning activities was that the students built their own analogies, describing cells as ‘natural bubbles’ (Hans) with cell membranes as their ‘natural barriers’ (Hans) which function as ‘emulsifiers’ (Konrad).

Furthermore, the visualisation of fat in water appeared plausible to the students because it helped them to get ‘kind of a 3D understanding’ (Hans) of the cell membrane which they earlier had ‘always thought of as a [one-dimensional] line’ (Jonathan) and apply it to their everyday lives: ‘I did in fact not think of that . wow. The first time I have thought about that emulsifiers are something I use in reality. Thank you’ (Jonathan).

Indeed, the students refined their concept of cells to their being compartments to enclose molecules such as ‘amino acids’, which would not be there without cell membranes. Hans explained this by constructing the following analogy: ‘You can have all the resources for a cake, but still you don’t have the cake’. Following this mode of thinking, they reconsidered their previous conceptions that plant calls do not have cell membranes.

Cell membranes are made of fats and proteins

As a result of learning activity 6 (sugar dissolves in water, but not in fat), the students extended the analogy to cell membranes: namely, that non-polar substances will be able to cross cell membranes as they are soluble in fat. Since the cell ‘wants’ (polar) glucose inside, the students deduced that the cell membrane also needed proteins to allow polar and ‘specific substances’ to be transported. Prompted by the teacher, the students consequently refined their candy model by including membrane proteins within the lipid bilayer. When the teacher then asked the students to rethink if all cell types have the same cell membrane composition, they reckoned that the protein composition of cell membranes would differ from cell type to cell type because proteins ‘decide’ what gets transported. Students’ utterances showed that in the course of the teaching experiments they would not give up their anthropomorphic and teleological explanations; however, their explanations increasingly included nuances of part-whole relationships at both the subcellular and the tissue level.

Cell membrane proteins enable communication with other cells

In order for the students to become aware of cell membranes’ function in enabling connection between cells, the teacher referred to the multitude of cells in human bodies, which the students had referred to earlier, and asked what enabled these cells to be organised in regard to each other.

The students quickly reckoned that cells need to communicate with each other, and that one way to do this is by hormones, for example, testosterone, as ‘messengers’. When asked about how this is achieved, the students deduced that it made sense that some cells would produce hormones, while only some other particular cells (‘hair cells of the lips or testicle cells’, Hans) could respond to these. Apparently, the instructional analogy that most hormones are like keys that fit into particular locks was plausible to the students, because they consequently reckoned that it was likely that only some specific membrane proteins would fit to the hormones.

Communication with other cells and the outer environment influences membrane protein composition

When asked how cells might respond to unusually high amounts of hormones, the students argued that ‘cells produce new things’ (Hans), which, they remembered, could only happen at the genetic level. Consequently, they reasoned that some messages at cell membranes must be relayed to the DNA in the nucleus which eventually leads to the production of new proteins. This again fostered the thought that the presence of proteins in the cell membrane can vary in response to external messengers. Evidently, the students had, in the course of these dialogues, reconsidered their previous conceptions in which proteins come from outside the body to one in which proteins are conceived of as products of our cells.

Triggered by the teacher's suggestion that external messengers need not necessarily be produced by the body itself, but can be from outside the body (as is the case for nicotine) (learning activity 7), the students constructed the analogy between other physical traits and their subcellular mechanisms, as the following dialogue illustrates:

301 ***Jonathan***:	What happens when people smoke, and use snus[7] a lot? After a while they won't experience the feeling of intoxication **anymore**. Why is that?
303 ***Hans***:	Yes, because they have so many proteins.
304 ***Jonathan***:	Ah, OK, so they must have . . .
305 ***Hans***:	. . . less effect. The effect **decreases**. And then you want more, and more, and more.
307 ***T:***	That's right. But that also means, of course, the more used you are to a high intake of drugs, the more proteins there are, and the longer it will take to get used to not having them. So, in consequence, the feeling of deprivation will increase. (.)[8]
311 ***Jonathan***:	Ohh, so, one gets intoxicated when the receptors are kind of overloaded? (.) And therefore, when you get addicted, you have a large number of receptors, and therefore crave for more nicotine? What a revelation!

The dialogue indicates that the students in the course of teaching had apparently revised their ontological presumption that the existing cell membrane structure is already the best fit and therefore does not change. This is apparent in the way the students employed new terms with a temporal connotation, such as *decrease*, rather than teleological explanations. Apparently what

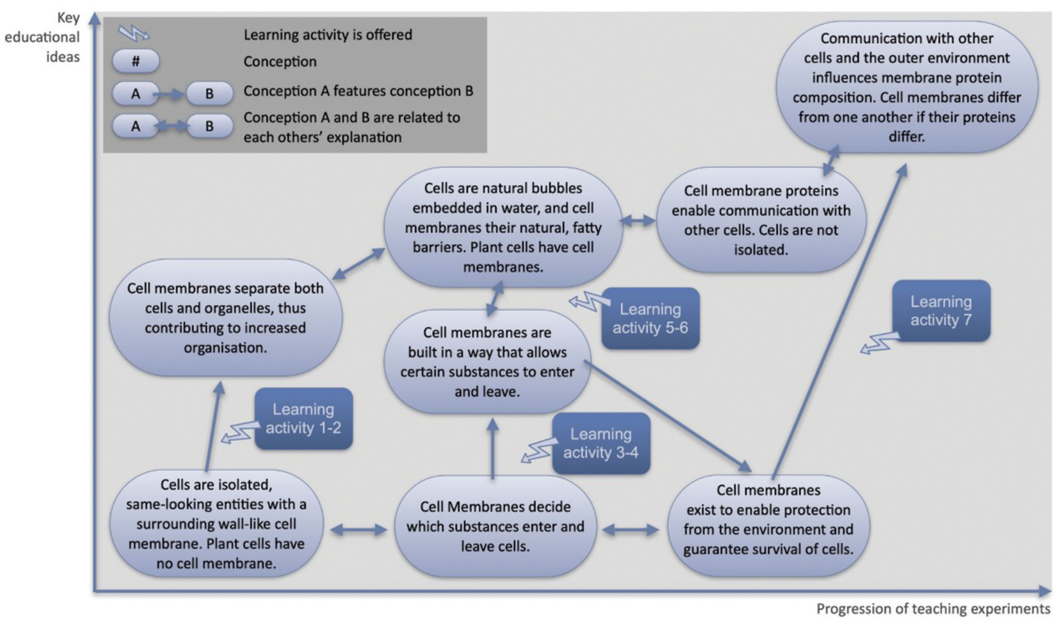


Figure 10. Student conceptions as they develop in the course of the teaching experiments while interacting with the learning activities. Arrows illustrate connections: single arrows illustrate development from one concept to another; double arrows illustrate when concepts are related to one another as explanations for a phenomenon. Adapted from .Weitzel and Gropengießer (2009)

was critical for this change was for the students to understand the role and origin of proteins. Combined with everyday examples, apparently familiar to the students, namely the change of physical traits ('feeling of intoxication'), it apparently made sense to them that there needs to be a mechanism ('more proteins') responsible for this change.

Jonathan's exhilarant 'What a revelation!' at the end of the teaching experiment illustrates students' increased awareness regarding their own learning process.

Discussion

Framed by the Model of Educational Reconstruction (Duit et al. 2012) and experiential realism (Gropengießer 2003; 2007; Lakoff and Johnson 1980), the aim of this teaching part of this study was to make the relatively abstract concept of CMB more accessible for upper secondary students.

In this regard, we have presented our findings concerning the educational construction of key ideas considering scientists' *and* students' conceptions of CMB as described in the literature (Figure 2Table 1), and indicated how these informed the design of analogy-based learning activities (Table 2, Figures 3–9). Identifying students' thinking pathways when they interacted with the learning activities (Figure 10) allowed us to generate novel knowledge regarding students' learning processes of this important scientific concept.

In line with findings from other studies exploring the learning processes of complex biological concepts, such as cell division (Riemeier and Gropengießer 2008) and evolution (Zabel and Gropengießer, 2011), our findings reveal that students can learn CMB when they are given the time and necessary conditions (such as meaningful learning activities and peer interaction) to develop their conceptions step-by-step (cf. Vosniadou 2014).

Our data suggest that learning CMB is difficult at least in part because students lack direct experiences with this concept – as opposed to perceivable macroscopic phenomena (e.g. the morphology or behaviour of insects) (Bahar, Johnstone, and Hansell 1999; Tibell and Rundgren 2010). However, since most scientific concepts are beneath students' perceptual awareness, this cannot fully explain the difficulties that students have with this topic. Our findings suggest that the difficulties were due: a) to students' inherent, embodied ontological,epistemological and conceptual presumptions; and b) students' lack of awareness of the limitations of these.

We found that students' inherent assumptions fostered both teleological and anthropomorphic explanations. Initially, the students postulated that cell membranes are one-dimensional barriers which exist for the function of actively protecting the inside of cells by deciding what leaves and enters them (cf. Clément 2007; Dreyfus and Jungwirth 1988).

Our findings suggest that these assumptions obscured what we, in line with existing literature (Howitt, Costa, and Anderson 2008; Johann et al. 2020; Rundgren and Tibell 2010), understand as the key educational idea of CMB: that cell membranes are biochemical barriers which, depending on their particular molecular make-up, allow for the existence and maintenance of living processes because they enable separation (due to the lipid bilayer) into distinct compartments at the same time as they enable the insides of these compartments to be connected (via proteins) to their outsides. For the students it seemed initially rather difficult to understand that the *apparent* perfect structure of cell membranes exists due to chemical features of their component molecules, and that these allow for functions which go beyond what students from their everyday experiences associate with barriers (i.e. static protection).

Other researchers have described comparable roots for learning difficulties in genetics where students were found to view genes as trait-bearing particles (Lewis and Kattmann 2004) rather than seeing them as chemical structures. Consequently, they did not recognise the need for processes which translate genes to proteins (Garvin-Doxas and Klymkowsky 2008; Lewis and Kattmann 2004).

Our data, in common with other researchers' findings (Rundgren and Tibell 2010), give reason to believe that critical requirements for students to overcome their CMB learning difficulties are for them:

(1) to understand cells (and membrane-bound organelles) in terms of compartments rather than bricks, because this guides their focus to a network of collaborating rather than isolated cells and increases awareness for a 'need' to enable such collaboration;
(2) to extrapolate between one-, two- and three-dimensionality to understand that cell membranes are parts of cells (and not their surrounding wall) and that lipids and proteins collectively constitute cell membranes;
(3) to understand that cells are embedded in aqueous environments which influence their structures. This guides students' focus to the (approximately) spherical shape of many cells ('natural bubbles') and thus gives new meaning to the term barrier as a 'natural' fatty layer;
(4) to understand that membrane proteins enable cell membrane function in terms of facilitating transport and communication among cells;
(5) to understand the origin of membrane proteins (from DNA) in order to increase awareness that cell membranes are dynamic constructs, constantly changing due to dynamic relations with the environment.

Practical implications

Existing studies suggest animated images as critical learning tools to visualise the dynamic character of cell membranes (Rundgren and Tibell 2010). Others emphasise, as a strategy for learning molecular genetics in general, making the different levels of biological organisation explicit and switching between these (Duncan and Reiser, 2007; Knippels and Waarlo 2018).

Similar to Riemeier and Gropengießer's (2008) proposal for the concept of cell division, our study proposes an approach which focuses on making explicit the different everyday meaning of terms that both students and scientists employ to help understand cell membranes (*separate, barrier, environment* and *protection*). To infer learning processes we suggest, in the light of our findings, looking at how to move students from rather passively using terms and concepts to using them more actively. This entails, for example, the generation of, from an educational point of view, meaningful terms (such as *compartment* and *organisation;* transcript lines 105–112) and analogies (e.g. 'natural barrier'), namely the use of 'old words' in a new context (e.g. separation of tasks, transcript lines 105–106) (Haug and Ødegaard 2014; Lancor 2014; Lemke 1990).

Our data build, in this regard, on other researchers' claims (Kersting et al. 2018; Duit 1991) that multiple analogies (both instructional and self-generated) can be powerful tools to visualise non-tangible relations – as is found in the molecular world of CMB (Tibell and Rundgren 2010) – as long as they refer to source domains that are adequate from both scientists' *and* students' points of views. Teaching with analogies thus requires that the teacher has sound awareness regarding the conceptions students hold (Driver 1989; Duit 1996; Vygotzky 1978) and how they differ (ontologically, epistemologically and conceptually) from scientists' conceptions (Vosniadou 2014).

This means that sometimes analogies (and learning materials in general) can be valuably employed at the expense of strict scientific correctness. For example, from a scientific viewpoint it may seem weak to compare cells/organisms to houses because houses are static constructs build by humans. However, for teaching purposes it can be powerful, because it made explicit the usefulness of separated rooms (cells) and their relation to each other (as in tissues). On the other hand, we raise the possibility that the candy material employed in learning activity 4 was suitable because this activity triggered a cognitive conflict among the students, which they found difficult to understand. Although the activity in itself seemed powerful to visualise step-wise how the features of amphiphilic lipids and membrane proteins determine cell membrane structure and function, we wonder whether the material was too abstract for the students to recognise the similarity between the polar character of lipids and the colour of the candies.

In regard to our findings, learning complex concepts in CMB is less about memorising in detail the functions of membrane proteins or studying diffusion and osmosis for their own sake (Marek, Cowan, and Cavallo 1994; Johann et al. 2020), but more about developing existing conceptions step-by-step (Vosniadou 2014). This does not entail students getting rid of existing conceptions featuring anthropomorphic and teleological explanations, but that they, depending on the context, can make use of mechanistic and process-related explanations.

Our data stress in this regard the importance of emphasising the roles and origins of proteins (Duncan and Reiser 2007; Verhoeff, Waarlo, and Boersma 2008) in school science curricula in the same way as genes and DNA, because these seem powerful in terms of making evident the relation between ultimate (evolution) and proximate (genes) causes for cell membrane adaptation (change) (Mayr 2004) as key characteristics of life.

Methodological considerations

Our study confirms that teaching experiments with students can be a conducive way to study learning processes and thus uncover the roots of difficulties when students hold similar conceptions regarding a subject (Komorek and Duit 2004). In our case, this meant that treating the student groups as 'communities of practice' (Lave 1991) was empirically and theoretically justified.

However, we note some limitations to this method. On the one hand teachers and researchers conducting such experiments must be well informed about students' conceptions of the given concept, as well as being skilled interviewers (Komorek and Duit 2004), with the ability to react to students' utterances at the 'right' moment. The researcher conducting the teaching experiments in this study had had sound previous experience of interviewing students regarding this particular topic. Furthermore, the researcher and the participating students had met a few times before the teaching experiments took place at the students' school. This contributed to establishing a relationship of trust between researcher and students which we considered critical regarding our aim for the students to articulate their thoughts honestly (Kvale and Brinkmann 2009).

In addition, our study was an experimental one conducted with a limited number of students and in small groups rather than in a normal classroom situation where there might be 20–30 students and a lesson would only last 50–60 minutes. That means that our findings only allow us to a certain degree to make informed statements about teaching and students' cell membrane learning in normal classrooms; we also did not investigate long-term-learning.

Conclusion

Cell membrane biology (CMB) has gained increasing scientific attention in recent years, not least as a result of the COVID-19 pandemic. It is important to consider students' conceptions in the design and evaluation of learning activities (Duit et al. 2012; Komorek and Duit, 2004; Vosniadou 2014) in order to make informed statements regarding how this important concept can be meaningfully communicated for upper secondary education (Utdanningsdirektoratet 2021).

Identifying students' thinking pathways (Zabel and Gropengießer, 2011) when interacting with learning activities designed within the Model of Educational Reconstruction and experiential realism (Lakoff and Johnson 1980; Gropengießer, 2007) allowed us to understand the roots of students' learning difficulties and how conceptual development took place. While existing studies suggest animated images to promote learning of CMB (e.g. Rundgren and Tibell 2010), our study emphasises analogy-based learning activities in order to foster students' conceptual development regarding the terms and statements they use to explain CMB (Duit 1991; Lakoff and Johnson 1980). Understanding the terms *barrier, gatekeeper* and *environment* in a new, mechanistic and process-based way enabled the students to relate these to a coherent conception of cell membranes.

The theory, methods and findings of our study may contribute to knowledge as to how students' conceptions can be used to design and evaluate theoretical- and empirical-based learning activities for rather abstract scientific concepts (cf. Kersting et al. 2018; Messig and Groß 2018; Riemeier and Gropengießer 2008). Whether the learning activities designed in this study can foster CMB learning in real classroom settings will have to be tested in future studies.

Notes

1. In this study we understand the field of genetics, sub-cellular processes (e.g. diffusion, osmosis) and cellular structures and processes (e.g. cell division) as cell biological concepts.
2. Since our literature review suggested that students seem to have few conceptions concerning the movement of substances across cell membranes (sometimes requiring the conversion of energy) or the dynamic interplay between proteins, we saw it necessary to first design learning activities regarding students' epistemological and ontological assumptions before eventually addressing subcellular transport processes and signalling pathways at cell membranes in more detail.
3. Terms which are highlighted in bold indicate conceptual development as understood in our study.
4. Three dots indicate that the students' talk overlaps one another.
5. Two dots indicates that the students paused to think.
6. The heads are meant to represent the polar, hydrophilic part (phosphate group), while the tails represent the non-polar hydrophobic fatty chains of the lipid
7. Snus is a tobacco product that is smokeless, and is placed as a moist powder inside the lips. It is very popular among young people in Scandinavia.
8. (.) means that some passages in the original dialogues are omitted.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Leonie I. Johann http://orcid.org/0000-0001-6293-6697
Fredrik K. H. Rusk http://orcid.org/0000-0003-1916-1499
Michael J. Reiss http://orcid.org/0000-0003-1207-4229

Ethical approval

This study was approved by the Norwegian Centre for Research Data (NSD). The approval number is 339,478.

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