

Article

Content-Based and Cognitive-Linguistic Analysis of Cell Membrane Biology: Educational Reconstruction of Scientific Conceptions

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Abstract: By means of their pivotal role in the outbreak of a variety of diseases, such as, recently, COVID-19, the molecular aspects of cell membrane function have gained considerable attention from researchers in recent decades. The resulting information explosion and the growing interdisciplinary character of cell biology seems, however, to not be represented in science classrooms. Hence, there appears to be a gap between what is scientifically known and what is actually taught in classrooms. Framed by the model of educational reconstruction (MER), the aim of our study is therefore to identify scientific core ideas of cell membrane biology from an educational point of view. This is achieved by conducting qualitative content analysis of relevant cell biology literature. By using Conceptual Metaphor as a theory of understanding, we additionally illuminate the experiential grounding of scientific conceptions. Our results propose that cell membrane biology can be structured into three core ideas, comprising *compartmentalisation*, *physical and chemical properties*, and *multicellular coordination* interrelated by evolution as a key aspect. Our results show that scientists conceive these ideas metaphorically. Embodied part-whole relations seem, for example, to lay the grounds for their understanding of biological function. The outcomes of the study may inform future cell membrane teaching.

Keywords: science education; cell membranes; conceptual metaphor; model of educational reconstruction; scientific clarification; molecular life sciences

1. Introduction

In order to successfully plan and accomplish fruitful teaching interventions, it is important for educators to have knowledge about the scientific content and methods in question [1]. However, increasing interdisciplinarity and the general information explosion that is connected to the molecular aspects of cell biology can make this a challenging task for educators [2–4]. Cell membrane malfunctioning plays a crucial role in the outbreak of a number of human diseases, such as many types of cancer, AIDS, and recently COVID-19. Investigating the structure and function of membrane components has, therefore, received much attention [5–8]. However, although cell (membrane) biology is part of the biology curriculum at upper secondary schools (high school, K-12) in Norway, there seems to be little focus on mediating cell membrane function in the context of underlying molecular aspects. Hence, there appears to be a gap between science content and what is actually taught in schools [3].

Framed by the Model of Educational Reconstruction (MER) [9], we do not understand science content as taken for granted for the purpose of instruction, but rather understand that it must get carefully reconstructed for teaching. This is achieved by a recursive process based on three components:

(I) the clarification of science content and scientists' conceptions, (II) the investigation of students' conceptions, (III) and the design and evaluation of learning environments. With the aim to make rather abstract science content more accessible for education by identifying scientific core ideas of cell membrane biology, this study is placed within the clarification of science content.

To identify scientific core ideas, we conducted qualitative content analysis [10] of relevant recent cell biology literature, such as college biology textbooks such as *Campbell Biology* [11] and *Alberts' Molecular Biology of the Cell*, and *Essential Cell Biology* [12,13], other relevant scientific literature in this biological field [5–8,14–20], but also historical research papers [21,22]. In the realm of moderate constructivism and Conceptual Metaphor Theory (CMT) [23,24], we understand science content to be constituted of scientists' conceptions, individual matters of thought, and these to be grounded in embodied results of lifeworld experiences. To understand the experiential grounding of scientists' conceptions we conducted a cognitive-linguistic analysis of traits of their written language as a window into these thoughts. CMT has proven fruitful to understand how scientists actually conceive abstract scientific concepts which lie beneath our conscious awareness [25]. This can be fruitful in the further course of reconstructing science content for teaching by means of illuminating potential learning barriers.

2. Conceptual Framework

2.1. *The Contributions of the Model of Educational Reconstruction (MER) for Identifying and Understanding the Scientific Core Ideas of Cell Membrane Biology*

The Model of Educational Reconstruction (MER), being greatly influenced by moderate constructivism [26] and conceptual change [27], emphasizes that science content has to be carefully *reconstructed* for instruction. This is achieved by equally taking into account both scientists' and students' perspectives. With that, the model stands with one foot in the scientific discipline and the other in education [9,28]. Predominantly in a German-speaking research community, the MER has proven fruitful for the reconstruction of numerous crucial, from a teaching point of view rather difficult subjects of science education including the concept of energy [29], evolution [30], plant nutrition [31], climate change [32] and cell division [33]. Given the importance of cell membrane biology in science classrooms at (Norwegian) upper secondary schools, and the reported challenges students meet in cell biology in general [33–36], we understand the MER as a suitable framework for this study. To condense, and thereby make scientific content on cell membrane biology more accessible for teaching, is also justified given the rising flood of scientific information due to its impact on our future health. The importance of understanding the molecular aspects of cell biology has, in this regard, been unhappily illustrated by the ongoing pandemic COVID-19, AIDS or increasing rates of certain cancer types.

The MER has three major components that are strongly connected with each other: (I) the clarification of science content, (II) the examination of student conceptions with regard to the topic of interest, and (III) the design and evaluation of learning environments [9,33]. The clarification of science content includes two closely linked processes: the *clarification of subject matter*, and the *analysis of educational significance*. By deriving the scientific core ideas of cell membrane biology, our study provides evidence within the MER's component of the clarification of science content. Thereby, we follow the MER's idea to critically analyse science content from the viewpoint of education. Therefore, we not only scrutinise science content itself, but also scientists' views of the nature of science, and the development of scientific processes by drawing on historical research articles. In the course of this, we also illuminate linguistic expressions which, although not impeding scientific understanding, can be misleading for learners [9]. The Conceptual Metaphor theory (CMT), which' contributions for this study we present in the next section, provides in this regard arguments for the sources of difficulties linguistic expressions can pose for learners.

2.2. Contributions of Conceptual Metaphor Theory for Cognitive-linguistic Analysis

In science education research [25,31,33,35] the Conceptual Metaphor Theory (CMT) [23,24] has proven to be a fruitful tool for the interpretation of conceptions by shedding light on their genesis. Informed by philosophy [37], cognitive linguistics and neuroscience [38–40]), it emphasizes that human cognition is based on sensory-motor experiences like our moving body in space or our experience with objects of different shapes. One way of conceptualising these experiences is by constructing neuronal-based image schemas [41]. Being grounded in lifeworld experiences, image schemas are also called embodied conceptions: preconceptual structures that lay beneath our conscious awareness and are therefore directly meaningful to us [42]. For example, the *container schema*, a result of our experience with containers of different shapes [41], is one of our most basic schemas for the distinction of inside- and outside matter divided by a barrier [43]. As a result of co-occurring experiences, there also seems to be a certain pattern of image schemas that structure our understanding [42]. For example, the *container schema* appears to frequently co-occur with other schemas, such as the *center-periphery schema*, which enables our mind to distinguish between areas that are or are not at the centre of our “conscious awareness” [41], (p. 20). Image schemas seem to serve as source domains for abstract conceptions we cannot perceive directly. This seems to be accomplished through metaphorical thought and is referred to in a neurobiological context as cross-domain mapping (source domain → target domain) [23]. In other words, the concrete results of our embodied everyday conceptions serve as source domains for the understanding of more abstract target domains in the micro- or macrocosmos [44]. As most scientific concepts are not directly perceivable to us, CMT has become an attractive tool in science education research to understand the experiential grounding of scientists’, and particularly students’ conceptions for a variety of different subjects [25,31], including cell biology [33]. To shed light on the embodied grounding of students and scientists’, respectively, thought has proven fruitful in understanding how learning barriers can arise; for instance, although scientists and students were found to draw on the same source domains to conceptualise climate change, they would map these differently to the target domain and thus achieve a different understanding of climate change [33]. Alternatively, by understanding that students apparently map the *container schema* to cells, educators could understand why learners would conceptualise these as brick-like [35,45], rather than flexible structures, which they are from a scientific viewpoint. Taking these considerations into account, we aim to better understand the genesis of scientists’ conceptions of cell membrane biology in this study: to shed light on how scientists actually conceive the abstract concept of cell membrane and how this can be valuable in the further course of reconstructing cell membrane biology for teaching. Following the idea of CMT, we, in this study, understand language as a window into our thoughts. The identification of traits related to (spoken and written) language can thus reveal the embodied source domains our (scientific) understanding is grounded in [46].

It seems, in this regard, that little is known about the embodied grounding of scientists’ conceptions related to cell membrane biology. However, as shown above, it seems that scientists often apply the same image schemas as learners, although mapping them differently to a target domain [25] Therefore, we expect to identify similar image schemas to those students’ were found to draw on in order to conceptualise (cell) biological concepts. We want to highlight some of these schemas, which we understand to be crucial for their conceptualisation in the following.

It appears that the *container*, and *center-periphery* schema play a crucial role in students’ understanding of cells. Based on the *these* schemas, for example, students were found to understand the nucleus as the most important structure of the cell, which has to be protected by the cytoplasm [35] from “exterior forces” [47]. As a source for biological understanding, the *container schema* also appears often to be applied together with the *source-path goal schema*. These two schemas together result in a more complex schema, also called *container-flow-schema* [32,46]. By means of enabling us to conceptualise the flow between different containers [25,48], students were found to apply these schemas to understand nutrition (uptake of nutrients from the environment into the body/plant) [49]. A schema that is mostly found in conceptions where certain properties of people are transferred to objects, is the

person schema [46]. For example, in order to conceptualise rather abstract and random substance movement, human behaviour often seems to play a role as a source domain for students' understanding of diffusion: molecules were believed to act deliberately like humans, for example, they would have the inclination to fill space, or water would move in order to equalise concentrations [50]. Furthermore, cells were imagined to eat and digest like humans [35]. In this study, the *person schema* is with regard to these findings understood in a broad context, whenever human features or abilities are applied as source domain. Of importance for scientists' understanding of cell membrane biology could also be experiences with changing objects (*transformation schema*) [51], which was found to enable learners' to understand processes of transformation, such as, for example, light that is in the end transformed into carbohydrates [31].

CMT has also proven conducive in terms of scrutinising linguistic expressions applied to communicate scientific concepts for the purpose of education. As scientific termini very often are metaphorical expressions, the search for the experiential source domain of these can be fruitful in terms of understanding that, often, these lead to associations differing significantly from what they are meant to convey scientifically. For example, the scientific term *cell division* puts stress on the lifeworld experience of division; In its everyday meaning, it refers to a decrease in number. Hence, learners are impeded to understand chromosome duplication as a prerequisite for cell division [33]. On the other hand, particularly concerning the molecular life sciences, it seems that many termini, such as, for example, *gene expression*, lack any lifeworld experience, and hence everyday meaning [2]. This lack of a source domain subsequently makes the conceptualisation of *gene expression* difficult to achieve. As a consequence for instruction, it therefore seems fruitful to not only apply scientific termini, and other linguistic expressions, uncritically, but reflect on the associations these do or do not convey [45]. In this respect, many expressions, for example, anthropomorphisms (human characteristics) and teleological expressions (purposes, and intention) [52,53] can in fact also be beneficial for learning. For example, when learners are helped to critically reflect upon their meaning. For the scientific rather abstract aspect of equilibrium (see also next section), Kattmann (2007) [53] suggests that metaphors such as "movement" or "interaction" can indeed be promotive for learning as they can function as an adequate bridge between our experience with balance, and the scientific concept of equilibrium.

As anthropomorphisms, and teleological expressions seem to play a crucial role in students' and scientists' understanding of the molecular life sciences [2], we give these particular attention in the course of scrutinising linguistic expressions in this study.

2.3. Status Quo of Cell-Biology Research in Science Education

To our knowledge, there are no studies illuminating the core content of cell membrane biology in the framework of the MER. However, there are a few studies that apply different approaches in the context of discussing this topic in a teaching context. We therefore find it relevant to include their considerations in our study. For example, in their empirical study on how to design fruitful visualizations for the teaching of transport mechanisms across cell membranes, Rundgren and Tibell (2010) [50] mention the following features as critical: (1) the dynamic bilayer architecture of the cell membrane which is shaped by its different components, (2) the barrier function that separates the "interior of the cell from its surrounding environment" (p. 233) and (3) the chemical features behind membrane semi-permeability and its effect on substance transport.

In other studies, [3] *compartmentalisation across membranes* connected to *equilibrium* as "key concept" [3] (p. 15) is suggested to be central to the discipline of molecular life sciences. The cell membranes' central role in maintaining equilibrium, which is crucial for a number of biological phenomena, such as the production of ATP (adenosine triphosphate), is also stressed by others [54]. Other aspects suggested [3] to be connected to the key concept of *equilibrium* are, for example, *information and communication through signaling*, *aqueous environments* by means of *buffering and solubility*, *regulation through transport binding*, and *the complexity of molecular structure* in terms of *shape, and polarity*. By means of the interdisciplinary character of molecular life sciences, existing studies [2,55] stress the need

to combine aspects of chemistry and biology with other subjects, such as mathematics and physics. Following this idea, others [56] demand not to teach diffusion and osmosis for their own sake (which in fact can be an interpretation of K-12 biology curricula in Norway) but in a broader context.

Framed by the MER and the CMT, the idea of this study is to identify core ideas of scientific conceptions of cell membrane biology from relevant literature in the field. Our aim is not to give an exact scope of the existing literature (which would be impossible), but to condense it from an educational point of view. In the course of this, we want to shed light on the embodied grounding of scientists' conceptions in order to illuminate potential learning barriers.

Based on these considerations, we address the following research questions:

- What core ideas of scientists' conceptions on cell membranes can be identified from literature on cell biology?
- What is the embodied grounding of these conceptions?

3. Methods

In order to identify and understand core ideas of cell membrane biology, we applied Qualitative Content Analysis [10] (QCA) and a cognitive-linguistic analysis framed by the CMT [23,24] to relevant science literature on cell membrane biology.

3.1. Data Collection

The global 9th edition of *Campbell biology* [11], more specifically chapter 7 and parts of chapter 6 and 42, functioned as a primary source for the identification of relevant science content. We deliberately chose to consult this educational textbook rather than a pure science textbook as it is widely used as standard literature in biology courses at universities worldwide and is written by scientists who place a strong emphasis on scientific correctness and educational focus at the same time. However, due to validity issues, particularly with respect to more recent findings in the field of cell and molecular biology, we also consulted other relevant literature such as college textbooks with a particular focus on cell biology [12,13] and recent cell biology literature selected based on their focus on membrane structure and function [5–8,14–20].

3.2. Analysis

Following the steps of the QCA [10], we first selected, and then condensed relevant text passages based on their content [57]. A further interpretation was achieved by means of content and cognitive linguistic aspects [24,51,58]. Thereby, we focused on the identification of image schemas, and analysis of linguistic expressions. A description of image schemas in a large body of science education and philosophy literature [41,44,59–62] thereby functioned as source for their identification in the text. To identify these, we focused on semantical structures such as prepositions, postpositions, verbs, body-part-metaphors, cases and morphemes. For example, prepositions such as *into* or *in* are usually indicators of the *container* schema.

Linguistic expressions that we, in the course of this analysis, found to be crucial for the communication of cell biology, were furthermore scrutinised critically on their everyday meaning. We did this by consulting the Anglophone online dictionary LEXICO (2019) [63]. In order to reduce our own "blindness" towards common scientific termini or sayings by means of our own background as scientists, and in order to reduce our individual subjectivity, we worked independently and compared our findings carefully.

An illustration of how we conducted the cognitive-linguistic analysis is shown in Table 1 below. The context between identified image schema (source domain), respective semantic text structure (proposition, metaphor, etc.), and target domain is illustrated by highlighting these in a particular, unifying colour. Furthermore, the everyday meaning of applied linguistic expressions is shown.

Table 1. Exemplary illustration of how image schemas (source domains) were identified and assigned to target domains.

Text Passage	Explanation	Source Domain (Image Schemas)	Target Domain	Everyday Meaning of Linguistic Expressions [63]
<p>“The plasma membrane is the edge of life, the boundary that separates the living cell from its surroundings”. “It controls traffic into and out of the cell it surrounds”</p>	<p>The prepositions <i>into</i> and <i>out</i> express movement of something separated by a barrier. Hence the goal of this is located inside, and outside, the cell. The embodied CONTAINER schema seems here applied together with the SOURCE-PATH-GOAL schema in order to understand the abstract plasma membrane metaphorically as a barrier between two environments. At the same time the PERSON schema seems to serve as the basis for the metaphorical understanding of plasma membranes as “controlling” guards.</p>	<p>container source-path-goal (container-flow) person</p>	<p>The function and task of the plasma membrane (PM) as a barrier and gatekeeper between the cell and its surrounding</p>	<p>Edge: <i>the outside limit of an object</i> Boundary: <i>A line which marks the limits of an area; a dividing line</i></p>

The strengths of qualitative content analysis are its systematic procedure and rule-governedness, which is meant to increase intersubjective verifiability and “measure itself against quality criteria and inter-coder reliability” [10]. Nevertheless, an individual interpreter’s idiosyncrasies will always be involved [64]. Therefore, two researchers were working independently. Through a subsequent alignment of their findings, we aimed to reduce these idiosyncrasies.

4. Results

We applied Qualitative Content Analysis [10] (QCA), and a cognitive-linguistic analysis [23,24] to define scientists’ core ideas of cell membrane biology and the embodied conceptions these are grounded in. As a result, we identified three crucial core ideas of scientists’ conceptions. These are presented in Section 4.1. Furthermore, we found scientists’ conceptions to be grounded in a variety of image schemas. These are presented in Section 4.2 The context between core idea, the respective underlying image schemas, and anchor examples from the text is shown in the Tables 2–4 in Section 4.2. Each core idea has its own table. The results of the critical scrutiny of linguistic expressions we found to be crucial for the communication of cell membrane biology are presented in 4.3 and summarised in Table 5.

Table 2. Relationship between the identified scientific core idea that *cell membranes allow life to exist by enabling compartmentalisation*, embodied grounding, and anchor examples from the text.

Core Idea	Image Schema	Experiential Grounding (Source Domain)	Target Domain	(Anchor Examples [11])
Cell membranes allow life to exist by enabling compartmentalisation	<i>container</i>	Objects	The plasma membrane as outer boundary	“The plasma membrane is the edge of life, the boundary that separates the living cell from its surroundings”.
	<i>person container-flow</i>	Human characteristics	The plasma membrane as facilitator for discrimination of substance exchange	“the plasma membrane controls traffic into and out of the cell it surrounds”.
	<i>path-source-path-goal -cycle-process container-flow container</i>	Directional bodily movement/objects	The formation of membranes as prerequisite for the evolution of life	“One of the earliest episodes in the evolution of life may have been the formation of a membrane that enclosed a solution different from the surrounding.”
	<i>transformation</i>	Objects	The translation of genetic information into proteins	“...a gene that codes for an immune cell-surface protein called CCR5”.

Table 3. Relationship between the identified scientific core idea that *chemical and physical properties allow for the biological function of cell membranes*, embodied grounding, and anchor examples from the text.

Core Idea	Image Schema	Experiential Grounding (Source Domain)	Target Domain	(Anchor Examples [11])
Chemical and physical properties allow for the biological function of cell membranes	<i>person container-flow</i>	Directional bodily movement/objects Human characteristics	Cells' need for nutrients, and their transport into, and out of cells	"The resources that animal cells require, such as nutrients and oxygen (O ₂), enter the cytoplasm by crossing the plasma membrane, metabolic by-products, such as carbon dioxide (CO ₂), exit the cell by crossing the same membrane".
	<i>component/integral-object</i>	Objects	Membrane function as a result of the interplay of its different components	"Phospholipids form the main fabric of the membrane, but proteins determine most of the membrane's functions".
	<i>locomotion container</i>	Non directional movement Objects	Random substance movement	.."the movement of molecules of any substance so that they spread out evenly into the available space. Each molecule moves randomly"
	<i>person force (enablement) container</i>	Human characteristics Bodily movement Objects	Active transport	"To pump a solute across a membrane against its gradient requires work; the cell must expend energy".
	<i>force process component/integral- object</i>	Directional bodily movement/objects	The process of developing a scientific model	The acceptance or rejection of a model depends on how well it fits observations and explains experimental results.

Table 4. Relationship between the identified scientific core idea that *cell membranes are key factors for intercellular in multicellular organisms*, embodied grounding, and anchor examples from the text.

Core Idea	Image Schema	Experiential Grounding (Source Domain)	Target Domain	Anchor Examples [11,18]
Cell membranes are key factors for intercellular coordination in multicellular organisms	<i>person force (blockage) container</i>	Directional bodily movement/objects Human characteristics	Different cell types have different membrane protein composition	"Over time we isolated and characterized more and more different cell types on the basis of the proteins they express on their cell membrane".
	<i>person contact</i>	Human characteristics	Membrane carbohydrates' role in cell-cell recognition	"Cell-cell recognition, a cell's ability to distinguish one type of neighboring cell from another, is crucial to the functioning of an organism."
	<i>balance container-flow</i>	Non-directional bodily movement	Balanced substance movement leads to equilibrium	... be a dynamic equilibrium, with as many dye molecules crossing the membrane each second on one direction as in the other".
	<i>transformation</i>	Objects	Protein synthesis	"Comparing their genes with the genes of infected individuals, researchers discovered that resistant individuals have an unusual form of a gene that codes for an immune cell-surface protein called CCR5".
	<i>source path goal container</i>	Directional bodily movement/objects	Membrane potential as source for energy	"The membrane potential acts like a battery; an energy source that affects the traffic of all charged substances across the membrane".

Table 5. Identified linguistic expressions about cell membrane biology with potentially ambiguous meanings.

Scientific Terms	Reasons for Ambiguity
barrier, edge of life compartmentalisation environment hierarchy the membrane "allows" and "controls" substance transport is "traffic"	everyday meaning differs from scientific meaning
Amphiphile Bilayer Equilibrium Homeostasis Concentration gradient Gene expression Fluid mosaic	unclear everyday meaning
biological (membrane), cell membrane; plasma membrane receptor, protein, hormone	lack of clarity and precision

4.1. Scientific Core Ideas of Cell Membrane Biology

In the following, we present the identified three core ideas of cell membrane biology. These are:

1. Cell membranes allow life to exist by enabling compartmentalisation;
2. Chemical and physical properties allow for the biological function of cell membranes;
3. Cell membranes are key factors for intercellular coordination in multicellular organisms.

In the following, each of the identified core ideas are described in depth.

4.1.1. Cell Membranes Allow Life to Exist by Enabling Compartmentalisation

Scientists seem to understand biological membranes as boundaries that allow for compartmentalisation into cells, respectively, organelles (eukaryotes), and thus the creation of distinct environments [11]. By means of at the same time enabling the discrimination of substance exchange between these environments, these compartments can still maintain homeostasis. Scientists understand that this compartmentalisation was crucial in the course of the formation of life. Therefore, they reason that the formation of membranes—the spontaneous assembly of amphiphilic lipids in aqueous environments—must have occurred early in the course of evolution. Since cells only can arise out of other cells, the cell membrane together with other certain features such as a cytosol, DNA is shared by all organisms.

4.1.2. Chemical and Physical Properties Allow for the Biological Function of Cell Membranes

In 1972, Singer and Nicolson [65] proposed the fluid mosaic model of membrane structure. Scientists understand this to be the result of a number of observations carried out by other researchers [21,22] during the 20th century. Although these did not have adequate tools to study the structure of cell membranes (electron microscopes), they deduced membrane structure by applying their knowledge about chemistry together with observations from previous findings.

Today, although continuously refined, the fluid-mosaic model still lays the ground for scientists' understanding of cell membranes as a dynamic bilayer (particularly lipids move on regular basis in the membrane) made of amphiphilic lipids with attached carbohydrates and attached or embedded proteins. This basic structure is conserved in all organisms. The model explains how membranes are enabled to discriminate in substance exchange by means of the chemical features of their components; thus, it is a "supramolecular structure" with properties that go beyond that of the individual molecules [11] (p. 177). The direction of substance transport depends on (electro) chemical forces. As substances have a constant motion, they will subsequently "spread out evenly in available space" [11] (p. 178). Therefore, when separated by a permeable membrane, they will move along their gradient from where they are more to where they are less concentrated; an equilibrium is reached when as many molecules cross the membrane in both directions. Thus, oxygen will enter the cell as long as it is consumed, and less concentrated in the cell. Charged substances will additionally follow an electrical force. As long as substances follow their gradient, their transport happens without the expense of energy, and is therefore called passive. This separation of charged molecules represents potential energy. It is actively maintained by the membrane, which subsequently can work as "batteries", storing energy that can be reused for the synthesis of chemical energy (ATP), or transmit nerve signals.

Thus, the membrane's role as barrier serves to keep all cell's components inside where they are needed, and also lays the ground for the establishment of distinct environments that can carry out different biochemical reactions. Its role as gatekeeper on the other hand guarantees the maintenance of homeostasis by enabling continuous supply, and waste of crucial substances (O₂ and CO₂), while it lays the ground for the regulation of others (such as e.g., ions).

4.1.3. Cell Membranes are Key Factors for Intercellular Coordination in Multicellular Organisms

Scientists put stress on the variation of membrane components. For example, different species are found to have different membrane lipid composition as an evolutionary adaptation to temperatures

in extreme environments (appropriate membrane fluidity is maintained by the ratio of saturated vs. unsaturated hydrocarbons). A difference in protein composition, on the other hand, results in membranes carrying out different functions in species and cell types. It is particularly protein composition that differs human membranes from these of prokaryotic cells. The information for different membrane compositions, as with all other cellular features, is stored in a cell's DNA. In multicellular organisms, with all cells sharing the same genome, it is the modification of gene expression that results in different cell types.

Scientists picture cells to be functional parts of the body that, together with their secretions (extracellular matrix, interstitial fluid) and according to their specialisation, assemble into tissues. Different tissues subsequently build organs, which build organ systems (such as, e.g., the respiratory system) Cell–cell recognition, carried out by membrane carbohydrates usually attached to proteins, enables cells to distinguish one type of neighboring cell from another, and with this, also reject foreign cells, such as viruses.

Human, and other higher animals' tissues, are characterised by protein connections (junctions) between cells in order to hold these together; this also allows substance exchange between them [12]. As in multicellular organisms, the majority of cells do not have direct contact with the external environment, but, with each other and the surrounding liquid, they depend on sophisticated transport systems in order to ensure nutrient uptake and waste disposal. It also means that it is particularly in these internal tissue environments that homeostasis, a steady state of chemical and physical conditions, must be maintained. This happens by means of signaling pathways between cells: specific membrane proteins (receptors) receive messages, such as, for example, growth factors (also proteins) from other cells. These signals then get step-by-step transmitted to their final destination (e.g., the nucleus) inside of the cell where ultimately a cellular response is triggered (e.g., different gene expression leading to proliferation). Through this mechanism, cells can change their behaviour in response to their respective internal environment. Disruptions in these pathways can therefore cause malfunctions, such as the uncontrolled proliferation of cells, which is one of the hallmarks of cancer. Receptors, however, do not only respond to intercellular messengers, but can, involuntary, also be the targets of foreign intruders, such as viruses, for example, the now well-known SARS-CoV-2. Some cell types, such as, for example, lung cells, express a particular receptor that gets used by the virus as a binding site in order to enter the cell. Severe symptoms of COVID-19 patients are therefore connected to distress in the respiratory system. Consequently, understanding structure and function membrane proteins (genomics, and proteomics) has gained much focus in research communities as they can be promising targets for drug development. In the particular case of COVID-19, specific receptor blockage is hoped to potentially prevent the entry of the virus. As a response to stimuli, membrane composition itself can also be affected (for example, by means of changing receptor density). The constant intake of substances such as nicotine, leads, for example, to an increase in nicotine receptors in brain cells. Thus, a constant high supply of nicotine is needed in order to guarantee the desired effect. Membranes, the components of which are continuously manufactured in the golgi-apparatus, and endoplasmatic reticulum (in eukaryotic cells) are therefore highly dynamic constructs enabled to adapt to environmental changes.

4.2. Different Source Domains Together Structure Core Ideas on Cell Membrane Biology

The results of the cognitive-linguistic analysis show that scientific core ideas on cell membrane biology are based on embodied conceptions. We could mainly identify variations of the *container*, *path*, and *person schema*. As an example, we found the *path* schema with its varying experiential source domains of horizontal movement (*source-path goal*), building the grounding for scientists' conceptualisation of, amongst others, temporal aspects, such as, for example, evolution. On the other hand, did we find schemas connected to experiences with human vertical "self-motion", such as walking, running, or jumping [66]; to lay the ground for scientists' understanding of random events, such as substance movement. Bodily movement and the encounter with "physical forces that push and pull us" [41]; (*force schemas*, such as *enablement* or *blockage* [41,47]) appear to serve as experiential source

domain for scientists' conceptualisation of, for example, energy consuming processes (e.g., substance movement against their concentration gradient). The *person schema* appears to be a result of a variety of experiences, such as, e.g., human intentional behaviour, by scientists, for example applied to conceptualise the membrane's gatekeeper function.

It seems that co-occurring experiences with part-whole relations (*component/integral-object schema*), and the flow between objects (*source-path goal, container*) serve as source domain to amongst others understand cell membrane function as a result of its structure.

In the following Tables 2–4, we show the context between each scientific core idea with its respective image schemas (e.g., *container*). With respect to the outlined results above, we also show what we identified to be the experiential source domain (e.g., object) of the respective image schemas and what we understood to be their target domain (e.g., the plasma membrane as outer boundary). Selected text passages from the literature used for data collection [11,18] are meant to serve as anchor examples to illustrate the respective image schemas and content.

4.3. The Everyday Meaning of Linguistic Expressions Connected to Cell Membrane Biology often Differs from Their Scientific Meaning

In the course of the cognitive-linguistic analysis, we found that the everyday meaning of many terms we identified as crucial for the communication of cell biology differs from what they are scientifically meant to convey.

To understand the origin of this phenomenon, we categorised these terms into three groups according to their different linguistic background: (I) terms with different meaning in everyday life, (II) terms with a lack of clarity and precision [67] and (III) terms without obvious reference to every life.

The results are shown in Table 5. In the following, we give an exemplary overview of examples belonging to these three groups, respectively.

4.3.1. Terms with a Different Everyday Meaning

Scientists do understand cell membranes metaphorically as barriers (see also 4.1). Thereby, they apply different metaphors, such as *barrier, edge of life, boundaries, and compartmentalisation*. By means of the everyday meaning of these terms, this can easily give the association of impermeability, which is significantly different to the scientific one: *barriers* in their everyday meaning refer to *obstacles that prevent movement or access* [63], while *compartments* can be understood as an *area in which something can be seen in isolation from other things* [63]. Furthermore, the term *edge* referring to *the outside limit of an object*, could give the association of a rather negligible cell membrane function, which, in reality, however, seems crucial for a cell's very existence from a scientific viewpoint.

We found scientists to apply a number of anthropomorphisms and teleological expressions in order to illustrate substance movement (*traffic*), cell membrane features (*allow, permit*), as well as the organization of cells in multicellular organisms (*hierarchic*).

Our results show that scientists understand the cell as a functionable part of the body. To denote biological organisation metaphorically as *hierarchic* [11] seems to oppose that conceptualization; it refers to different ranks [63] and creates the scientifically unfavourable understanding of cells having the lowest status.

Traffic in its everyday meaning refers to *vehicles moving on a road* [63]. Traffic is usually of directional character as a result of human's intentional behaviour, and its regulation does not discriminate between vehicles. Therefore, this term could lead to the association that the same accounts for substances; however, an important aspect of substance movement is its unintentional, and usually non-directional, aspect, which results in (electro)chemical forces over the cell membrane.

The mentioned anthropomorphisms by which the cell membrane is attributed, such as *allow* and *permit*, illustrate the membrane as a human that consciously decides what is "permitted" and what may enter or leave the cell. This seems to impede the scientific understanding of substance discrimination as a result of chemical features.

4.3.2. Terms with a Lack of Precision and Clarity

We often found scientists to employ same termini for different concepts (such as *environment* for tissues, and the outer environment), as well as different termini for the same concept (*plasma membrane*, *cell membrane*). Often, in its everyday meaning, the term *environment*, refers to the “natural world, as a whole or in a particular geographical area, especially as affected by human activity” [63]. Therefore, this meaning differs significantly from the micro-environment in tissues which refers to neighbouring cells and surrounding interstitial fluid. In this regard, we also noted that what in reality from a chemical sense is a protein, is denoted with a variety of different termini with regard to its biological function, such as *enzymes*, *hormone*, *messenger*, or *receptor*. The everyday meaning of *protein* might in this regard rather be connected to its function as dietary compound. In line with previous findings [67], we found that *plasma membrane*, *biological membrane*, and *cell membrane* were applied interchangeably.

4.3.3. Terms Without an Obvious Reference to Every Life

Many scientific termini in the context of cell biology are expressions that lack an everyday meaning, since they are of Latin or Greek origin and/or they are artificially constructed.

For example, when being unaware of their translation, it might not be clear that termini such as *fluid mosaic* or *bilayer* (Latin: *bi*: two) refer to the arrangement membrane components, while termini as *phospholipid*, *amphiphilic* (Greek: *amphi*: on both sides; *philos*: loving) or *hydrophilic* (Greek: *hydro*: water) refer to the chemical features of a molecule being a component of this membrane. This is also the case with the termini *equilibrium* (Latin: *aequi*: ‘equal’; *libra* ‘balance’) and *homeostasis* (Greek: *homoios*:like; *stasis*: stopping), which play an important role in scientists’ understanding of membrane function. Often, scientific termini seem to be constructed artificially by means of the assembly of seemingly distinct source domains, such as *concentration gradient*, *gene expression*, or *fluid mosaic*.

5. Discussion

5.1. Scientific Core Ideas of Cell Membrane Biology are Interrelated by the Key Aspect of Evolution

Framed by the Model of Educational Reconstruction’s (MER) [9] idea of *scientific clarification*, the present study aimed to identify scientific core ideas of cell membrane biology. This was achieved by applying qualitative content analysis [10,68]. In order to unveil the genesis of the scientists’ conceptions, we furthermore performed a cognitive-linguistic analysis framed by the conceptual metaphor theory [23,24]. In the course of this, we also scrutinised the genesis of linguistic expressions we understood as crucial for the conceptualisation of cell membrane biology.

Our results show that cell membrane biology can be structured into three core ideas: 1. cell membranes allow life to exist by enabling compartmentalisation, 2. chemical and physical properties allow for the biological function of cell membranes, and 3. cell membranes are key factors for intercellular coordination in multicellular organisms. These findings are supported by other studies with regard to the key aspects of cell membrane biology [2,3,50,54,69]. Outcomes of the study also indicate that scientists have to employ metaphorical thought in order to conceive these ideas. Thereby, we found that scientists apply linguistic terms and expressions that are often crucial for scientific understanding but can potentially be the source of confusion and misunderstanding in a teaching context.

We understand the identified core ideas to cover multiple phenomena of cell membrane biology. Furthermore, we see the concept of evolution of more complex life forms to be the connecting key aspect that interrelates all three of them. This is illustrated in Figure 1 below. This means that, from a scientific viewpoint, the formation of cell membranes has to be understood as the prerequisite for the evolution of different life forms.

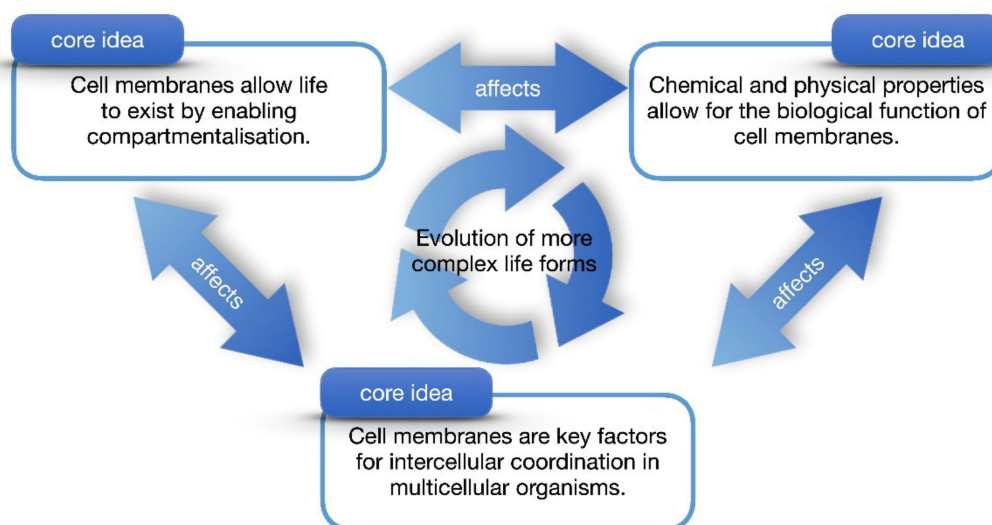


Figure 1. Evolution of more complex life forms as key aspect to interrelate core ideas of cell membrane biology.

Our findings extrapolate Howitt et al. (2008) [3] and Rundgren et al.'s [50] proposal to understand *compartmentalisation* as a core idea of cell membrane biology: it is by the physical separation of distinct environments that these could carry out different biochemical reactions. This laid the grounds for evolution of different life forms from the earliest quite simple prokaryotic organisms to later more complex eukaryotic cells with different membrane enclosed compartments, and subsequently the evolution of complex, multicellular organisms. Our results also support Tibell et al.'s (2010) [2] emphasis on understanding cell membrane function (and much of biological function in general) in light of *chemical and physical properties* and consequently the stress they place on the three-dimensional character of cell membranes. This is also reflected by the historical research into membrane structure in the 20th century, where scientists knew of the existence of cell membranes, however, lacking the necessary equipment to study them, deduced their structure from what they knew about chemistry.

It appears that the crucial function of cell membranes as generators for chemical energy (it is a battery) and the transmission of nerve impulses has to be understood as a result of a combination of physical forces and chemical features. That is, the tendency of molecules to move in space, and the separation of molecules in general, and of opposite charges in particular.

Thereby, membrane proteins play a key role in regulating homeostasis—a steady internal condition—by maintaining equilibrium [3]. In multicellular organisms, this is amongst others maintained by *intercellular coordination*. Different membrane proteins function as a sophisticated regulation system, while membrane carbohydrates function as recognition system. Thus, homeostasis in tissue micro-environments, and subsequently the whole organism, is maintained. By means of regulating their gene expression in order to, for example, increase receptor density, cells are enabled to react upon changes. A breakdown of any of this system's key components can therefore lead to severe malfunctions, such as uncontrolled cell proliferation (cancer), which can only affect multicellular organisms. The variety of different receptors, which is vital for the complex interplay of multicellular cells, also makes these prone to tricky alien intruders, such as coronaviruses, who can misuse specific receptors for their own entry into the cell. For scientists, it seems natural that scientific understanding always is a result of many scientists' contributions. In most cases, it is the hypothesis that best takes into account existing observations that is most likely to be accepted by a community of scientists, such as the fluid-mosaic model of membrane structure having only undergone slight changes since its proposal in 1972 [14].

The results from the cognitive-linguistic analysis [23,24] clearly show that scientists base their understanding of cell membrane biology on embodied conceptions.

It seems that scientists thereby often combine different lifeworld experiences. For example, directional bodily movement (*source-path goal*) with those of objects (*container*) which enables them to conceptualise cell membranes metaphorically as *barriers* [41] and regulating *gatekeepers* of substance exchange between environments (*container-flow schema*). Our results, thus, extrapolate Niebert and Gropengießers (2013) [25] finding that the *container-flow schema* is a crucial source to understand the dynamic character of exchange processes between distinct objects (the atmosphere, the cell, and its outer and inner environment, respectively). In other words, our findings indicate that the same embodied structures are applied for the conceptualisation of macroscopic (carbon cycle) and microscopic phenomena. This makes sense as neither are perceivable by us directly (electron microscopic pictures of cell membranes still look like two lines with something in it).

Directional movement appears also to be the experiential source for scientists' understanding of the dynamic character of membranes in regard to the motion of their components (particularly lipids), but also their continuous renewal (e.g., by the integration of membrane proteins from the golgi apparatus). Opposed to directional movement, human movement in a non-directional, vertical sense (like jumping) [66] seems to be an important experiential source domain for scientists' conceptualization of randomness, such as in the case of an individual substance's movement. However, it is the combined experience of directional and non-directional motion that appears to enable scientists to understand some important concepts, such as diffusion and lipid bilayer assembly in aqueous environments. While, on the other hand, their understanding of *forces* seems grounded in individual's movement *against* the directional movement of the population, which requires energy.

Experiences with part-whole relationships (*component/integral-object schema*) seem to be a crucial source domain for scientists' understanding of functionality by means of the interplay of components. As an example, this accounts for their understanding of cell membranes as *supramolecular structures* with properties beyond that of the individual molecules. This conceptualisation is on equal basis to their conceptualisation of cells being functionable parts of the bodies. It did, therefore, not come as a surprise that we did not find the *center periphery* schema to play a role in scientists' understanding, since they understand all parts as equally important for the whole.

Membrane formation, as a prerequisite for the evolution of different life forms, plays a crucial role in scientists' understanding. Based on their experience with continuous, directional bodily movement (*process schema*), scientists appear to achieve an understanding of temporality [70] and evolution as a still ongoing process.

In line with findings from other studies [2], we found that scientists use experiences with human characteristics and behaviour (*person schema*) by means of anthropomorphisms and teleological expressions to build the source domain for a variety of different concepts. It appears that these often build the source for target domains which were also grounded in experiences with forces (*force dynamic image schemas*), such as, for example, substance movement. Particularly with regard to these different source domains for the same target, we often found scientists' linguistic expressions to be ambiguous. Although this ambiguity is unlikely to affect scientists' understanding, we want to discuss its implication in a teaching context in the next section.

5.2. Implications for Teaching

Our results support existing literature [2,3,50] in clearly showing that the increasing focus on the molecular aspects of cell membrane biology require sound knowledge of several disciplines, such as chemistry and physics, but also an integrative understanding of evolution, genetics and physiology. We, therefore, emphasize that, in order to successfully implement cell membrane biology in K12 classrooms, traditional borders between these disciplines and different biology topics should be transcended. Cell membrane biology in K12 classrooms in Norway seems to mainly focus on specific phenomena, such as diffusion and osmosis. However, our findings extrapolate Marek et al.'s (1994) demand to implement these in a broader context by, for example, putting stress on living system's strive for homeostasis. Moreover, we want to draw attention to the potential of teaching cell membrane

biology in the context of well-known phenomena, such as, recently, COVID-19, but also many kinds of other diseases, such as cancer or AIDS. To point out the severe malfunctions that can arise with regard to the breakdown of cell membrane function might be a way towards understanding how it usually regulates homeostasis.

The outcome of the cognitive-linguistic analysis indicates that particularly lifeworld experiences of part–whole relations, distinct types of bodily movement and objects have the potential to serve as adequate source domains for the understanding of cell membrane biology as they enable us to understand its dynamic, three-dimensional character. However, from what is described in literature [35], it appears that learners are more likely to apply distinct experiences as single source domains and map these differently to the target domain; for example, by mapping the *container schema* as sole source domain to cells, it is no wonder that these are conceived as brick-like [35].

The challenge for teaching seems, therefore, to identify and subsequently trigger adequate mappings that take into account scientific core ideas, and students' existing embodied conceptions. In the course of this, we mean that the careful use of language, and the creation of new experiences should play a key role [53,67,71]. Our results extrapolate existing findings [2,53] that many linguistic expressions applied by scientists have the potential to be counterproductive for learning when having an ambiguous meaning. This, we found, can be due to a lack of precision or clarity [67] (e.g., *plasma membrane* vs. *cell membrane*), inducement of inadequate mappings (e.g., the cell membrane *knows*), or no reference to lifeworld experiences (e.g., *fluid mosaic model*). For example, we found a broad specter of anthropomorphisms and teleological expressions to have an opposed meaning to what they are meant to convey scientifically [33]. By, for example, denoting cell membranes as *knowing* and *permitting* there is a danger that learners are triggered to associate these with intentionality and consciousness. If learners are not prompted to reason upon differences between cell membranes and humans [53], this could undermine their scientific understanding (chemical features of the membrane's components are responsible for its function). However, given the abstract structure, and complexity of its function, one is bound to denote cell membrane function and structure metaphorically.

This highlight educators' need to be aware of their students' existing conceptions [27] in order to being able to carefully scrutinise the fruitfulness of linguistic termini applied in science classrooms [33,45]. Thereby, it should be a teachers' task to uncover underlying conceptions and make them accessible for learners [25,31,46]. In the course of this, we stress the importance of creating new experiences that have the potential to prompt learners to reflect upon the meaning of existing embodied conceptions, thereby rethinking the fruitfulness of these. This seems of particular importance in cell biology with regard to many linguistic expressions (such as *fluid mosaic* or *bilayer*) lacking any reference to lifeworld experiences. As proposed by Tibell and Rundgren (2010) [50], a promising approach may be animated visualisations, instead of still images, in terms of highlighting the three-dimensional character of the membrane. These could be combined with other activities where, for example, different part–whole relationships are illustrated.

5.3. Limitations of the Study and Further Research

The Model of Educational Reconstruction (MER) [9] provided a framework for this study. A critical aspect of this model is its recursive process towards the fruitful reconstruction of science content. This includes three closely related steps: (a) a scientific clarification, (b) the examination of student conceptions, and (c) the design and evaluation of learning sequences [9,33]. Guided by the aim to identify scientific core ideas of cell membrane biology, our study was, however, limited to the scientific clarification and was therefore to some degree devoid of the usual recursive process. However, we mean that it has the potential to inform future cell membrane teaching fruitfully by not focusing on science content alone, but also looking at possible ambiguities from the viewpoint of education. This can contribute to the further (re)construction of fruitful learning content for cell membrane teaching. We want to stress that we found the combination of theoretical considerations of the MER, and those of conceptual metaphor [23,24], which has proven to be valuable in similar studies [31,33], to be very

fruitful. By understanding the genesis of scientists' understanding, it enabled us to shed light on potential learning barriers in the context of cell membrane teaching. We finally want to emphasize the need to further investigate into student conceptions on cell membranes and conduct empirical studies on the fruitfulness of our proposed core ideas for cell membrane teaching.

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