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Students' conceptions of water transport

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Understanding diffusion of water into and out of the cell through osmosis is fundamental to the learning and teaching of biology. Although this process is thought of as occurring directly across the lipid bilayer, the majority of water transport is actually mediated by specialised transmembrane water-channels called aquaporins. This study investigated a total of 175 Taiwanese and Swedish students' conceptions of water transport across the cell membrane, and at what level of biological organisation students represented such knowledge. A free response instrument was employed to generate students' written and diagrammatic responses. Analysis of the data resulted in the emergence of four distinct categorisations of students' conceptions. Corresponding analysis of students' diagrams revealed varying levels of scale for representing and expressing water transport conceptions. The results revealed that many students lacked an awareness of the role of specialised water channels in water transport and thought that the majority of water molecules traversed the hydrophobic membrane through direct diffusion. Our findings suggest that teaching the topic of diffusion and osmosis be aligned with current scientific discovery.

Key words: Students' conceptions; Water transport; Aquaporins; Cell membranes

Introduction

Science education research has revealed a range of difficulties with students' understanding of microscopic concepts in biology (e.g. Chang, 2007; Ferrari and Chi, 1998; Kindfield, 1993/1994; Schönborn, Anderson and Grayson, 2002, Tibell and Rundgren, 2010). Therefore, it is crucial for biology educators to concentrate focused efforts towards disseminating the fundamental ideas behind new discoveries in the molecular life sciences during teaching and learning. This process requires educators to stay abreast of whether the knowledge students gain during learning correlates positively with present scientific discovery. By considering one such crucial biological discovery, this study investigates students' conceptions pertaining to water transport across the cell membrane.

The concept of water transport across the cell membrane

According to Campbell and Heyer (2007 p. 296), *"Introductory text-books state that the cell membrane is "semi permeable". When you learned that membranes are made of phospholipids, you also learned that only hydrophobic molecules can pass through cell membranes. No charged or polar particles can pass through, not even a proton. Yet you probably also learned that water, a polar molecule, can pass through a cell's membrane. This sets up a logical contradiction that is rarely discussed."* Understanding the diffusion of water

into and out of the cell through osmosis is fundamental to the learning and teaching of biology (e.g. Cook, Carter and Wiebe, 2008). However, biology education research has documented a range of students' alternative conceptions associated with osmotic concepts (e.g. Tekkaya, 2003; Odom and Barrow, 1995). In fact, a popular study conducted by Johnstone and Mahmoud (1980) showed water transport to be one of the most difficult topics encountered by secondary school and university students.

Although the movement of water through the cell membrane is typically thought of as occurring *directly* across the lipid bilayer, the major proportion of osmosis is actually regulated by specialised water channels called *aquaporins* (Agre *et al*, 1993). This Nobel Prize-winning discovery has shown, for example, that aquaporins facilitate reabsorption of 90% of the aqueous component of the glomerular filtrate in the kidneys. In fact, aquaporins can facilitate water movement through the cell membrane at a rate of 3×10^9 water molecules per second (Campbell and Heyer, 2007). Although some water may traverse the cell bilayer directly through simple diffusion (e.g. Fettiplace and Haydon, 1980), this volume is low when compared to the amount that can potentially traverse through aquaporin channels (Agre *et al*, 1993).

Given that much biology education research has considered students' understanding of osmosis (e.g. Tekkaya, 2003; Odom and Barrow, 1995), to our

knowledge, no study has investigated the nature of students' conceptions about the role of aquaporins in water transport, and whether these conceptions correlate favourably with contemporary scientific knowledge.

Different representational levels of biological concepts

According to Jones *et al* (2008, p. 409), "scale is one of the thematic threads that runs through nearly all of the sciences and is considered one of the major prevailing ideas of science". Indeed, one overriding feature of biology is the representation of knowledge at different systemic levels of organisation and scale. Recently, Johnstone (2010) has suggested that one of the main difficulties associated with learning science is that learners must 'move' between different representational levels that range from the 'macroscopic' to the 'symbolic'. Constructing knowledge at different representational levels is considered a crucial criterion for the successful learning of biology (Bahar, Johnstone and Hansell, 1999).

Research aims

Based on the motivation above, this study responds to the following research questions:

1. What are students' conceptions of water transport across the cell membrane?
2. At what representational levels do students externalise their knowledge about water transport?
3. What are the differences between how students with high and low prior knowledge express their understanding of water transport?

Methods

Study participants and educational background

We purposefully selected the research participants as follows. On one hand, we were interested in investigating students' understanding of water transport from at least two different international perspectives. On the other hand, we wished to investigate students' conceptions of water transport across a continuum that ranged from 'low' to 'high' levels of prior knowledge. In this respect, a group of Taiwanese non-science majors represented the low prior knowledge end of this continuum, while a group of Swedish biochemistry students were representative of the high prior knowledge end.

Of the total 175 students that participated in the study, 138 students were non-science majors from Taiwan, enrolled in their first or second year at university, who last formally encountered the subject of biology during the 10th grade of their secondary education. The remaining 37 participants were Swedish third-year university chemical biology majors.

Research design

In order to probe students' conceptions so that they revealed what "came to mind" without being "led" into giving a particular answer, we collected free response data through written verbal responses coupled with

student-generated diagrams (SGDs). Apart from obtaining written responses, the biology education literature has shown SGDs to be a powerful technique for exposing how students' mental images are related to their understanding of biological concepts (e.g. Kindfield, 1993/1994; Reiss and Tunnicliffe, 2001). Given this approach, we used the following free response probe to explore students' understanding of the movement of water across the cell bilayer:

Draw a detailed and labelled diagram to fully describe how water molecules move into and out of an animal cell. Explain your drawing as completely as possible.

Each group of participants delivered their responses to the probe in Mandarin and Swedish, respectively. Our motivation for, and validity of, the use of this open-ended instrument as a data-collection tool is supported by the work of Reiss and Tunnicliffe (2001), who also employed a single task for generating a data corpus that required 158 participants to "Draw what they thought was inside themselves" (p. 385).

Data analysis

Analysis of students' responses consisted of two stages namely, an *inductive category development* stage (e.g. Lincoln and Guba, 1985), followed by a *deductive category application* stage (e.g. Mayring, 2000). The inductive stage consisted of analysing the written responses and SGDs, wherein a system for categorising students' conceptions of water transport emerged from the data corpus. An iterative categorisation of students' responses proceeded according to a phenomenographic approach (Marton, 1994). Here, we discerned different conceptual categories in light of how students experienced the phenomenon of water transport in comparison with the current scientific view. The deductive stage comprised of categorising the SGDs according to three representational levels defined as follows (cf. Gilbert, 2008; Bahar *et al*, 1999):

- The *macroscopic* level ("MA"): MA is a representation of the "world-as-experience" that is tangible and directly accessible to the senses. In the present study, expression of MA may correspond, for example, to the representation of the morphology of a human organ in an SGD.
- The *microscopic* level ("MI"): MI represents the entities that serve as a basis for the tangible macroscopic level, such as the cells that constitute properties of human tissue, or the molecules and ions that constitute a chemical solution, entities that cannot be observed directly with the naked eye. Students might express MI in a drawing by representing the nucleus of a cell or the bilayer constituents of a cell membrane.
- The *symbolic* level ("SYM"): SYM consists of the qualitative abstractions used to illustrate entities existing at the microscopic level, such as chemical formulae and mathematical equations associated with,

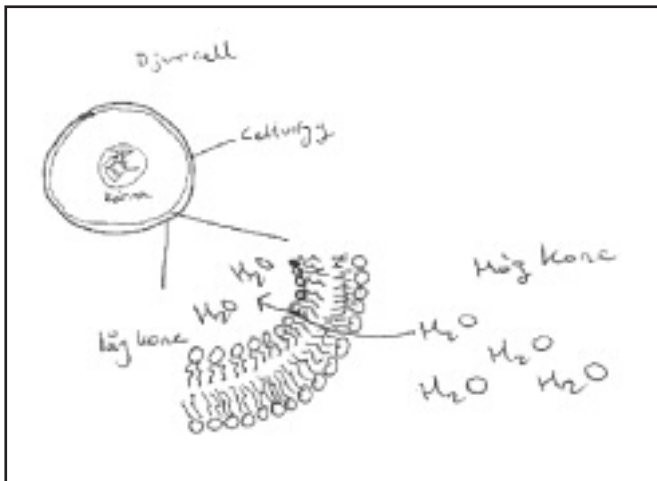
for example, a “mole” of substance in a chemical solution. Students might express SYM by representing a water molecule as “H₂O”.

Results

Levels of students' conceptions of water transport across the cell membrane

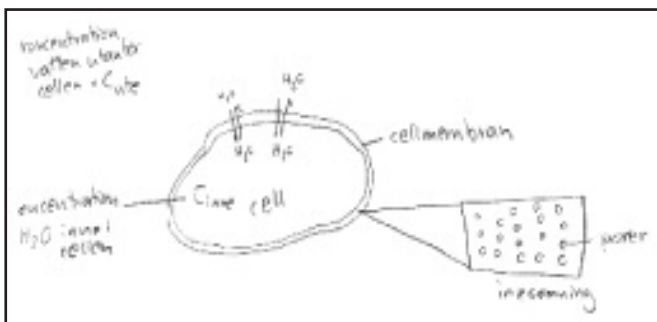
Inductive analysis of the data revealed a four-level categorisation system (Levels 0 – 3) for defining students' conceptions of water transport through the cell membrane. Descriptions of the levels of conceptions are presented in Table 1.

The following are datum examples of written responses and SGDs that capture the definition of each level of the four-level categorisation system (Table 1). With respect to Level 0, consider the following SGD and textual response obtained from two different Swedish students, respectively:



“I don't know if I can draw this, but it is called osmosis and is related to concentration inside and outside the cell. The cell membrane is permeable so that the water molecules can diffuse through it where the concentration of something is at its highest, so that the concentration can be lowered there. Water is ‘working’ against the side with high concentration.”

Consider the following student's SGD and accompanying response that represents understanding corresponding to Level 1 of the categorisation system (Table 1):



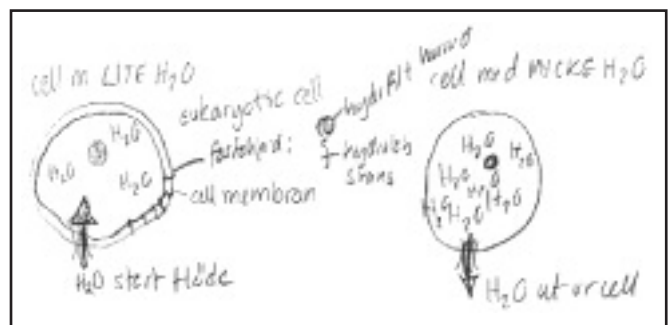
“The flow of water is controlled by the osmotic flow, that is, if the concentration of water is higher outside the cell,

Table 1. A four-level categorisation system for students' conceptions of water transport across the cell membrane.

Level	Description of conception
Level 0	Students are of the view that all, or the major part, of water transport into and out of the cell occurs directly via direct diffusion through the cell membrane.
Level 1	Students are of the view that the major proportion of water transport takes place at locations such as “holes”, “pores” or “pump-like” structures in the cell membrane, but do not provide any scientific insight into the structure or mechanisms of such locations; and/or, provide an unscientific hybridised account of the former.
Level 2	Students are of the view that the major proportion of water transport takes place through certain transport channels in the membrane, but do not mention that the channels are exclusively specialised for water transport; and/or, inappropriately fuse different modes of transport.
Level 3	Students are of the view that the majority of water molecules move into or out of the cell through specific transmembrane channels that are selective and specialised for water transport alone (with or without necessarily mentioning the term <i>aquaporin</i>).

then water will diffuse in through the cell membrane. If the concentration of water is higher inside the cell, then the flow is reversed. Water can diffuse out and in through small pores in the membrane.”

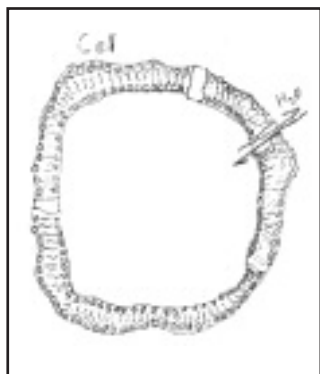
The following datum is indicative of a student's understanding categorised at Level 2 of the categorisation system (Table 1), where students did not exclusively denote any specialisation to water transport channels and often mixed otherwise separate cellular transport mechanisms into their accounts of water movement across the membrane:



“Water is drawn into the cell depending on osmotic concentration. If there is a lot of water in the cell then water is driven out of the cell and if there is a lack of water the water is driven outwards. This is a process which is not energy consuming as the water is driven by the osmotic gradient. The cell strives towards a water balance otherwise there is a risk of lysis. Water is hydrophilic and this makes it hard for water to pass the hydrophobic cell membrane (which contains

phospholipids). Therefore I believe that water transport channels are maybe needed, maybe that H₂O is drawn in together as a co-molecule, when another substance is taken into or out of the cell."

Lastly, the following excerpt and accompanying SGD demonstrates understanding of water transport that corresponds to Level 3 (Table 1):



"Water flows through the cell walls [membrane] through specialised channels. The direction depends on the concentration of dissolved substances outside and inside the cell. The system tries to ensure that the concentrations are equal both inside and outside the cell."

Incidences of students' conceptions at each level

The results presented in Figure 1 below indicate that 65% (52/80) of the Taiwanese students exposed an understanding of water transport corresponding to level 0, where it was thought that the majority of water enters the cell directly across the lipid bilayer. Twenty students (25%) suggested that water molecules are transported through a "hole" or "pore" in the membrane, a conception ascribed to level 1 (Table 1). Only 8/80 students (10%) mentioned that the movement of water molecules was related to a transmembrane mediatory "channel", but failed to explain that such channels constituted a specialised form of transport (level 2, Table 1). Regarding level 3, none of the Taiwanese participants exposed the conception that water transport occurs through (aquaporin) channels that were specialised for water transport only.

Amongst the Swedish participants, 14/37 students (38%) provided explanations for water transport that corresponded to level 0 (Figure 1). Two students (5%)

provided answers corresponding to level 1, while 13 students (35%) expressed an understanding of water transport captured at level 2 of the framework. Despite the fact that the Swedish students could be regarded as experienced learners in this domain, only eight of them (22%) formulated an explanation of water transport across the membrane that could be categorised at level 3.

Representational levels of students' conceptions of water transport across the cell membrane

Coupled to the emergence of four categorisations for describing students' conceptions, we also analysed students' drawings of water transport according to the three representational levels outlined in the methods section above.

Our analysis suggested expansion of the defined 'micro' (MI) category into two *further* sub-levels namely, the 'micro-cellular' (MIC) and 'micro-molecular' (MIM) levels, as a means of capturing students' externalisations of water transport in more representational detail. In this respect, a student's drawing that incorporates the micro-cellular level (MIC) conveys 'whole' cells or distinctive 'parts' of a cell, such as organelles or the cell membrane. A student drawing at the micro-molecular level (MIM) conveys molecular phenomena by depicting the structural or functional properties of at least one individual molecule. With respect to these designations, consider an example of the analysis of the SGD presented in Figure 2 below.

SGDs from 101 Taiwanese students' were analysed according to the representational levels outlined above. As displayed in Figure 3 below, 86% of students constructed diagrams that depicted water transport mainly at the MI (84%) and SYM (2%) levels. In addition to these levels, 14 % of students generated diagrams of water transport at the MA level, which included *pure* MA (7 persons) as well as *combined* MA-MIC (1 person), MA-MIC-SYM (5 persons) and MA-SYM (1 person) depictions. None of the 37 Swedish students represented their drawings of water transport at the MA level, but rather did so at the MI (95%) and SYM (5%) levels. As a

Figure 1. Incidences (%) of students' conceptions of water transport across the cell membrane according to the four-level categorisation system.

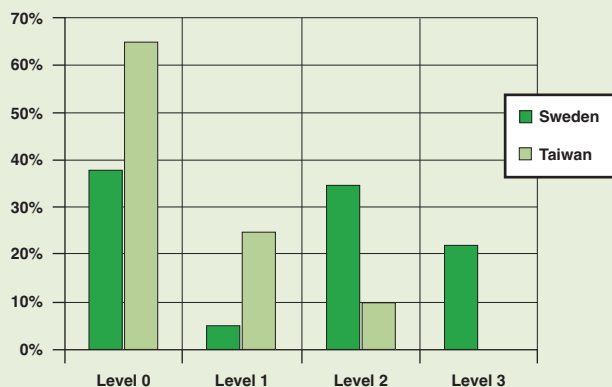
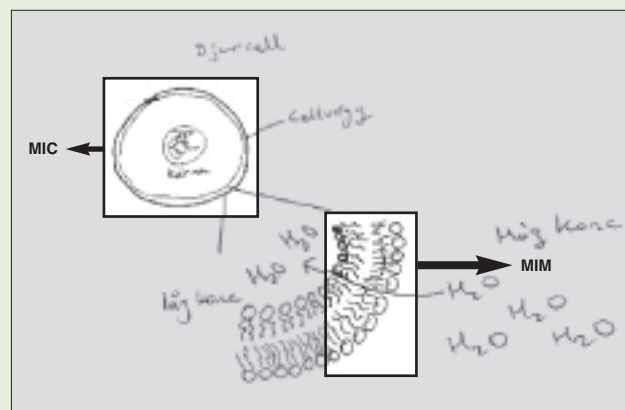


Figure 2. An example of a student's drawing that simultaneously exhibits the micro-cellular (MIC) and micro-molecular (MIM) levels that comprise the micro (MI) level of representation.



“ 138 students were non-science majors from Taiwan, enrolled in their first or second year at university, who last formally encountered the subject of biology during the 10th grade ”

Figure 3. Comparative incidences (%) of students' SGDs that depicted the different representational levels.

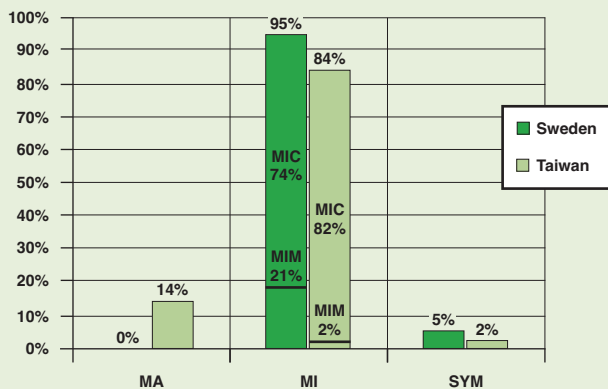
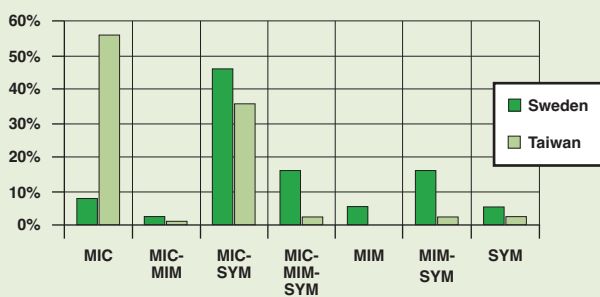


Figure 4. Relative incidences (%) of students' levels of representation inherent in their drawings expressed at the micro (MI) level.



means of comparing the differences between Swedish and Taiwanese data at the MI level, Figure 3 shows that the Swedish students externalised a higher incidence of representations at the MIM level (21%) than did the Taiwanese students (2%).

In addition to the results presented in Figure 3, of the representations expressed at the micro (MI) level, many of the Taiwanese students depicted water transport at the MIC level (Figure 4). This result included 57% of drawings that were categorised as pure MIC, as well as combined representational levels depicted by 1% at MIC-MIM, 36% at MIC-SYM and 2% of students at the

MIC-MIM-SYM level. Only 2% of the Taiwanese students represented the MIM level through combining drawings of this level together with SYM. Regarding the SYM level, 2% of students depicted a representation of water transport at a purely SYM level (Figure 4). With respect to analysis of the Swedish SGDs, the majority of students (74%) generated representations of water transport across the cell membrane that were categorised at the MIC level. Here, 47% of the drawings were categorised as combined MIC-SYM representations, and three at the pure MIC (8%) level. However, a larger proportion of the Swedish students (26%) produced drawings that contained molecular and symbolic (mainly formulae-related) information than did their Taiwanese counterparts. Among all the Swedish SGDs above, six students (16%) constructed drawings at the combined MIC-MIM-SYM level, two (5%) at each of the SYM and MIM levels, respectively, six (16%) at the MIM-SYM and one (3%) at the MIC-MIM level. A comparison of the SGD data arising from these incidences across the Taiwanese and Swedish student groups is presented in Figure 4.

Discussion

With respect to the Taiwanese students, the findings of the study reveal a decreasing incidence of each level of students' conceptions of water transport (Table 1) from level 0 (65%) through level 3 (0%) (Figure 1). This trend suggests that only a limited number of these students' conceptions have been aligned with the scientific fact that a large proportion of osmosis occurs via channel-mediated water transport. In addition to demonstrating that almost two-thirds (65%) of the Taiwanese participants are of the view that water diffuses directly through the lipid bilayer, we should highlight the point that although these students had last studied biology in the 10th grade, it appears that the pivotal discovery of aquaporins may have been absent from teaching of this topic. In this regard, an informal analysis of the four most widely-used biology textbooks at the 10th grade level in Taiwan revealed the *absence* of any presentation of transmembrane water transport concepts whatsoever. For the 11th grade level, although textbooks from the

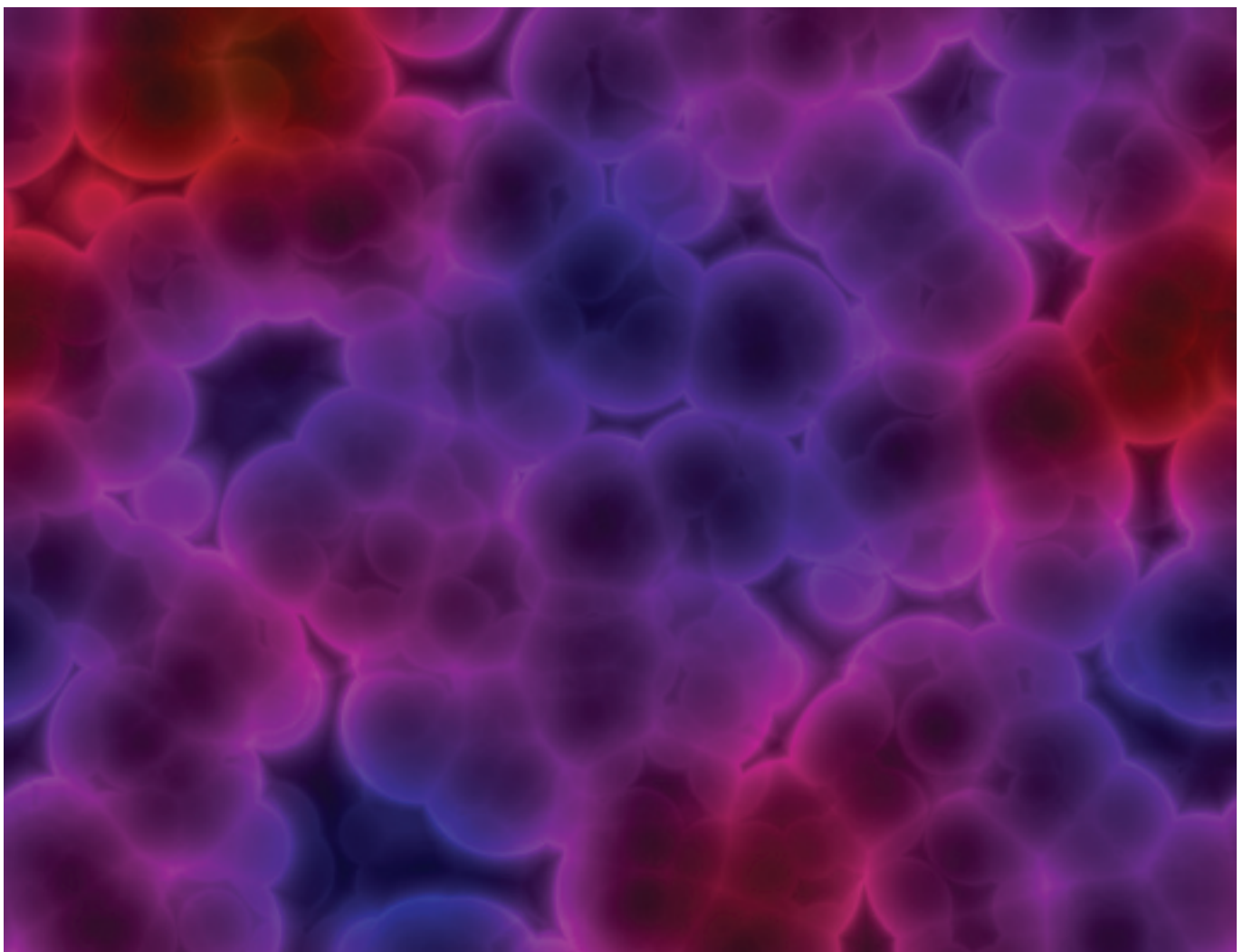
same four publishers exposed the three mechanisms of membrane transport (diffusion, facilitated diffusion and active transport), only one textbook specifically expressed the role of aquaporins in osmosis (Chang Rundgren, unpublished).

Of particular interest to a fundamental understanding of basic membrane transport processes, is the unexpectedly high incidence of conceptions exposed by the Swedish biochemistry majors that corresponded to level 0 (Table 1). While these tertiary students could be considered experienced learners of molecular life science topics, surprisingly, 38% of the participants did not provide an explanation of water transport connected to any notion of specific channel-mediated diffusion (Figure 1). Although the Swedish biochemistry students had been exposed to teaching that took cognisance of the current scientific view (as evidenced by students who nevertheless exposed level 3 ideas), many students exhibited the apparently robust conception (e.g. Ferrari and Chi, 1998) that all water molecules involved in osmosis diffuse directly through the lipid bilayer itself. We are of the opinion that this observation may well stem from secondary school teaching approaches where dialysis tubing is often used as a popular analogue for communicating ideas about osmosis. Here, superficially mapping the idea of a "semi-permeable" dialysis barrier

to the notion of a cell membrane *in vivo*, may cause students to erroneously think that *polar* water molecules will always simply traverse directly (and rapidly) across a *hydrophobic* bilayer. This interesting finding could be supported by an analysis of the seven most widely used Swedish upper secondary (grade 11 and 12) biology textbooks (Larsson & Rundgren, unpublished). The analysis revealed that two of the textbooks did not mention any water transport mechanism whatsoever, while four described water transport in terms of direct diffusion across the bilayer alone. Only a single textbook explicitly stated that the majority of water molecules are transported via specialised water channels.

In terms of the levels of representation of water transport expressed through SGDs, 14% of Taiwanese students presented their understanding at the MA level (Figure 3). This finding could perhaps be explained by non-science majors' use of everyday phenomena to make sense of scientific concepts (Chang, 2007). Furthermore, 96% of Taiwanese students who drew their explanations at the MI level externalised their understanding of water transport at the micro-cellular (MIC) level (Figure 4). This

The diffusion of water in and out of cells by osmosis is fundamental to the teaching of biology.



result could be because Taiwanese textbooks tend to convey biological concepts at the cellular, rather than molecular level of organisation.

Interestingly, although tertiary biochemistry textbooks consulted by the Swedish students predominantly convey water transport through representations pitched at the molecular level (e.g. Campbell and Heyer, 2007), almost half of the students still generated their diagrams at the combined MIC-SYM level (Figure 4). The high incidence of MIC-SYM representations could account for the relatively low expression of understanding at Level 3 (Figure 1), since explanations involving the properties of phospholipids and the polarity of water molecules at the molecular level are vital for constructing an understanding about aquaporins.

Educational implications

The low incidences obtained for level 3 conceptions (Figure 1) across both the Taiwanese and Swedish groups could suggest that current means for communicating the scientific fundamentals of water transport to students may be largely ineffective. Therefore, biology educators may require innovative teaching interventions that could for example, systematically pitch visualisations at different levels of biological organization as an agent of change for adjusting students' robust conceptions (Schönborn and Bögeholz, 2009). A point of interest in this regard is the relatively simple exposure of older students' limited understanding of water transport through science education research methods normally used for exposing the understandings of much younger students. An improved communication of water transport across the membrane also requires 'gaps' between progress in science and teachers' scientific knowledge to be bridged, by actively disseminating new biological discoveries into teachers' pedagogical toolkits via appropriate forums such as school-based workshops.

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