The potential for haptic-enabled interaction to support collaborative learning in school biology

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Abstract. This paper discusses the rationales and design considerations for developing the use of haptics (virtual touch) for learning aspects of cell biology in secondary schools. The paper considers issues in understanding concepts in cell biology and how a 3-D environment enabled by haptics could support learning of difficult concepts. In this endeavour, a number of educational and design challenges need to be addressed. First we need to identify the level of detail and realism that will support learning and visualisation rather than confuse through its overcomplexity or create misconceptions through oversimplification. Secondly we need to integrate the use of the 3-D environment into classroom teaching by identifying relevant curriculum and pedagogical challenges and solutions. Significant design challenges include navigating the content and scale changes involved in moving between the visible, microscopic and nanoscale in an intuitive and realistic way and enabling collaborative learning.

Introduction

In this paper we discuss the aims and rationales for developing the use of haptics for learning biology in a virtual environment. Haptics provides the additional sense of touch to the existing sight and sound in a virtual environment enabling students to perceive texture and forces directly. Furthermore haptics enables students to directly manipulate objects far more realistically than is possible through interfaces such as mouse and tracker ball etc. Thus haptics could support rich interactive learning experience in 3-D simulations of situations that are not accessible in real life. There is some empirical and theoretical support for such a proposal. Firstly, there is evidence of the benefits of multi-sensory learning in comparison to uni-sensory learning (Shams & Seitz, 2008). Multi-sensory refers to using more than one sense and typically in Technology Enhanced Learning (TEL) this has been visual and aural but now that opportunities for haptics are increasing, using visual and haptic or all three senses is feasible. Secondly, it is possible that haptic interaction will support visualisation, an important cognitive skill in science (Wai, Lubinski, & Benbow, 2009), as discussed later in this paper. A specific theory that may account for some potential for improved learning associated with haptic support for visualisation is Dual Coding Theory (Paivio, 1969, 2014) which proposes that there are distinct but interconnected systems for different sensory modalities and they act synergistically.

Where Haptic-based TEL has been used in tertiary education its potential has been demonstrated in teaching fundamental science concepts including engineering control (Okamura, Richard, & Cutkosky, 2002) and molecule docking (Persson et al., 2007). There has been very limited uptake of haptic technologies in secondary education although Minogue and Jones (Minogue & Jones, 2006) have a comprehensive review of the potential in this area.

We have chosen the domain of cell biology for three main reasons: 1) it is critical for understanding biology as a whole (Verhoeff, Waarlo, & Boersma, 2008); 2) misconceptions are common in cell biology (see for example Flores, Tovar, & Gallegos, 2003; Tibell & Rundgren, 2010) and 3) the structures and processes of cell biology are too small to be examined directly so manipulation of virtual models may be particularly valuable. In this project we are focusing on the understanding and concept development needed for learning science where there are specific opportunities for haptic interaction to transform experiences. For example, as scales change from cells to organs, the forces encountered change from electrostatic to Newtonian. The haptic devices can relay these forces in an interaction and the virtual world can enable different views and experiences. In essence, when interacting with the membrane of a cell the student could switch from the viscosity dominated world of microorganisms to the familiar world where mostly we don't stick to surfaces. We propose that students will gain deepest understanding if they can control this interaction and actively manipulate objects to explore their properties and test hypotheses.

Furthermore we propose that enabling collaborative learning and particularly focused discussion is important for supporting this developing understanding.
Our aim in this project is to examine whether haptic-enabled virtual environments could enhance learning beyond that achieved through visual means and how this might be realised. In order to investigate this possibility we are developing a rich 3-D learning environment with a stimulating visual and tactile (haptic) interface that encourages cooperation and provides students with opportunities to hypothesise and explore complex scientific concepts (Tokatli et al., 2016). We have adopted a rapid prototyping approach with formative evaluation using participatory research. Schoolteachers are included in the design team and are authors on this paper. Their students are working with us to test and evaluate designs and prototypes.

In this paper we first review some challenges for learning biology and common misconceptions of cell biology that might be addressed by haptic interaction. Then we review briefly previous evidence of relevant aspects of TEL contributing to science learning and specifically of visualisation, which is particularly relevant to understanding of structures and processes that cannot be observed directly. The design challenges for the development of the haptics-enabled educational scenario are examined.

Issues in Understanding of cell biology

Difficulties and misconceptions associated with learning in cell and molecular biology have been studied over many years (Flores et al., 2003; Tibell & Rundgren, 2010). From a review of the evidence Tibell and Rundgren concluded that students' difficulties in these areas were different from conceptualisations in other areas such as physics and chemistry. Specifically the evidence suggested that fragmentation of knowledge and difficulties in connecting and using knowledge are more significant than alternative conceptions so Tibell and Rundgren proposed that choices of appropriate communication tools such as language and visualisation would be crucial in developing understanding (ibid.). Furthermore, in relation to using visual representations and models Tibell and Rundgren stressed the importance of developing students' ability to interpret visualisations (visual literacy).

A review by Flores et al (2003) examined previous evidence of conceptual problems for students at primary, secondary and undergraduate level and found a range of difficulties which tended to persist despite teaching. Furthermore they surveyed 1200 students at secondary level in order to gain an integrated view of students' difficulties with cells and cell processes. Comprehension problems that they identified are listed in Table 1.

the articulation between structural units cells and multicellular organisms
the functioning of cell membrane
confusion between photosynthesis and respiration
the classification of organisms as simple and complex and incorrect inferences made about the cell
confusion between meiosis and mitosis
the differentiation of concepts like genetic code, chromosome, DNA, etc.
structural organization and external morphological differences are transferred to cell processes
problems with recognizing a variety of cell forms and size

Table 1 Areas in cell biology that present student comprehension problems (Flores et al., 2003 page 273)

Results of the work of Flores et al (2003) confirmed previous studies and highlighted aspects which might be addressed through learning in virtual environments. Specifically there is confusion between the sub-cellular, cellular and super-cellular levels of biological organisation with understanding processes. Students also have visual image difficulties when observing cells under the microscope and tend to recognise cells as a series of square elements or a tangle of lines and dots. Furthermore there is a persistent anthropomorphic view of processes and assigning of intentionality to cell function. A review of evidence of the value of animations in supporting students' developing understanding and visualisation of cell membrane structure and function and a detailed qualitative study (Rundgren & Tibell, 2010; Tibell & Rundgren, 2010) identified the importance for learners in interpreting visualisations of: 1) prior conceptual knowledge; 2) the specific design of the animation; 3) the use of symbolism and 4) the amount of information presented simultaneously. However despite some limitations the detailed qualitative study of students learning with an animation of cell membrane transport provided some evidence that the animation was important for providing students with deeper conceptual understanding of: 1) spatial features and the extrapolation between 2-D and 3-D; the stochastic and dynamic nature of the process and 3 the complexity of molecular interaction (Rundgren & Tibell, 2010).

In recent years there has been much development of various 3-D software models of cells and interactive applications . However, in our partnership schools where 3-D software models of cells are used (see for example R. Johnson, 2011), teachers continue to report similar challenges in learning/teaching in cell biology. More specifically, teachers have reported that students have no particular difficulty learning the names and functions of parts of the cell at a surface level of knowledge but developing deeper understanding of scale and processes is more challenging. For example students who had studied A-level biology did not realise how small a protein molecule was in comparison to a mitochondrion. These anecdotal accounts are also supported by findings of an investigation into first year university students' perceptions of scale and size (Vlaardingerbroek, Taylor, & Bale, 2014). Many students appeared to tacitly assume that textbook diagrams presented cellular components in true relative size, leading to widespread interpretative problems with regard to scale and absolute size (ibid.).

Interacting in a virtual environment with objects that are normally only visible when magnified poses challenges for students in understanding magnification and relative sizes. There has been little research on the use of magnification in learning by school-aged students but one small-scale study of children aged 10-13 suggested that students have significant difficulties understanding magnification and need guidance, which is often not provided by teachers, in interpreting what they see through magnifiers and microscopes (Marsh, Parkes, & Boulter, 2001). de Oliveira & Galembeck's (2016) analysis of mobile applications that might be used for learning cell biology identified that, like textbooks, virtual resources represent scale very unrealistically in order to focus on conveying generic information about objects such as cell organelles.

The changes in size as students might navigate through a virtual cell are illustrated in Table 2. Technically the scaling process for the computer graphics rendering is not difficult (Tokatli et al., 2016) but intuitive means for interacting with the content and navigating the scale changes are required. This might include, for example, a means of measuring objects within the software and/or a slider to change magnification.

	Typical Measurements	**Approximate average dimension in metres**	**Magnification used for viewing object**
Diameter of a pin head	1.5 mm	$1.5 * 10^{-3}$	Not needed
Cheek epithelial cell (diameter)	50 -80 µm	$6 * 10^{-5}$	100-400 X (light microscope)
Nucleus	7.5-10 µm	$8* 10^{-6}$	100-400 X (light microscope)
Mitochondrion (length)	3-10 µm	$6* 10^{-6}$	Electron microscope
Mitochondrion (width)	0.2-1 µm	$5* 10^{-7}$	Electron microscope
Ribosome	25 nm	$2.5* 10^{-8}$	Electron microscope
Microtubules (diameter)	20 nm	$2* 10^{-8}$	Electron microscope
Plasma Membrane (thickness)	6- 9 nm	$7*10^{-9}$	Electron microscope
Microfilaments diameter	3-6 nm	$4*10^{-9}$	Electron microscope
Membrane protein	3-6 nm 20-110 nm	$4*10^{-9}$ $60*10^{-9}$	Cryo-electron microscope

Table 2 Dimensions of scale in cell biology

The scaling issues in relation to the physical properties and dynamics that will be accessed through haptic interaction are more technically complex as explained in Tokatli et al (2016). Here we focus on the learning affordances. As the students probe through the plasma membrane into the epithelial cell important forces for them to understand are elasticity and its importance in osmosis. As they encounter the cytoplasm viscosity is the dominant force. These forces can be simulated by modelling the membrane as a simple boundary but as the students interact with the structures scaling becomes important. If we use the analogy of surgery, typically microsurgery operates at 5-40 magnification and is used for fine manipulation of tissues e.g. repairing nerves and small blood vessels. Biologist do use some micro-dissection techniques for separating out cell types and this might be simulated with magnified epithelial cells but would require great dexterity. In order to operate within individual cells it will be necessary to simulate a change in size of the students in relation to the cell. Furthermore the students would need to understand this transformation perhaps by showing the size in relation to other known objects, possibly a tooth in this case. The haptic interface that we propose to use in our future work will provide two points of contact thus making it possible for students to grasp objects with their fingers within a scaled-up virtual cell. For school children we believe that it will be beneficial to scale up and thus avoid the need for very fine dexterity.

Cognitive Challenges for Learning Science and the value of TEL

Studies have suggested that using simulation software may enable cognitive change in a range of topics including the particulate nature of matter (Snir, Smith, & Raz, 2003), understanding of image formation by lenses (Tao, 2004), genetics (Soderberg & Price, 2003) and trajectory motion (Jimoyiannis & Komis, 2001). However the situation is quite complex and computer-based solutions are not necessarily successful. For example, when reviewing the evidence for the value of animation alone (i.e. without interaction), for enabling students to learn, Morrison et al., (2002) found that many animations failed to improve learning beyond that achieved by static representations. They attributed this to their finding that animations were often too fast or too complex. Therefore in designing a haptic-enabled environment we need to consider the specific cognitive skills that may be required for successful engagement as well as ways in which productive interaction can be facilitated.

One important cognitive skill for understanding structures and processes in science is visualisation which is one of the elements of spatial ability. It has long been recognised that the ability to visualise and to manipulate objects in the imagination is a crucial skill for learning science (Gilbert, 2005; Tuckey & Selvaratnam, 1993). Linn and Petersen (1985) described spatial visualisation as one of the many processes which contribute to spatial ability, which they defined as "skill in representing, transforming, generating, and recalling symbolic, non-linguistic information" (p.1482). Spatial visualisation was distinguished by Linn and Petersen (1985) as a category often connected with spatial ability tasks that involve complicated, multistep manipulations of spatial information, and although these tasks can involve the processes required for other categories (spatial perception and mental rotations) they are distinguished by the possibility of multiple solution strategies.

Recent compelling evidence for the importance of spatial ability in STEM fields comes from Wai, Lubinski and Benbow's (2009) study of over 400,000 randomly sampled students, in which they found that those with degrees in STEM fields and who pursued scientific occupations had higher spatial abilities at adolescence than those with non-STEM degrees. For example, those at doctorate level in the physical sciences were 0.45 standard deviation units greater than the mean in spatial ability, whereas those in the humanities grouping were -0.15 standard deviation units below the mean. The authors concluded that spatial ability is a salient characteristic of those who achieve particularly well in STEM fields. There is also evidence of correlation between general academic achievement and motor coordination in students aged 9-12 years (Lopes, Santos, Pereira, & Lopes, 2013).

There are also gender issues in spatial ability. In a meta-analysis of spatial studies, Linn and Petersen (1985) found that males outperform females on mental rotation tasks and they attributed this difference to their preferred strategies: males were more likely to use a 'holistic strategy' that relied on visualizing the whole object whereas females were more likely to use an analytic strategy based on a systematic, stepwise approach.

TEL can support the development of visualisation skills in geology through the use of specific tasks in multimedia simulations (Piburn et al., 2005). In engineering education a variety of tasks, both paper-based and in multimedia environments, such as multi-view drawing, object rotations, paper folding and combining solids enabled students to develop their visualisation skills (Sorby, 2009). Thus according to both Piburn et al.(2005) and Sorby (2009) visualisation skills can be developed through training, and with the ability to visualise concepts of area, volume, distance, translation, rotation, and reflection comes an ability to learn relationships and functions that will enable the student to conceptualise and hypothesise.

In summary, spatial ability and particularly visualisation skills are linked with academic achievement especially in STEM fields. Visualization has been suggested to aid student understanding of complex processes because it assists in the conversion of an abstract concept into a specific visual object that can be mentally manipulated (McClean et al., 2005). There is a possibility, based on the Dual Coding Theory (Paivio, 1969, 2014) that the addition of a haptic interface to a 3D virtual environment may support the development of visualisation skills. However the evidence, reviewed briefly above, suggests that school students' spatial ability may vary considerably and some training may be necessary before students can successfully navigate the 3-D space and make good use of the haptic-enabled 3-D simulation software. This was borne out in pilot studies for this project (Tokatli et al., 2016; Webb et al., 2016) and we found that it was useful to provide a simple familiarisation task in order to acquaint students with manipulation within the 3-D virtual environment.

Collaborative learning

While haptic feedback interactions between individual learners and technology have been shown to be beneficial for the development of skills (San Diego et al., 2012), reviews and analysis of the use of TEL have shown that increased understanding of complex structures and processes is likely to be achieved through interactions between students as they engage with the technology and learn collaboratively (Cox & Webb, 2004; Webb, 2008).

Collaborative learning is known to have a positive impact on students' learning (D. W. Johnson, Johnson, & Stanne, 2000; Lee, Linn, Varma, & Liu, 2010) but productive interactions between students are not easily achieved (Barron, 2003; Chan, 2012) and appropriate learning situations are challenging to implement (Bell, Urhahne, Schanze, & Ploetzner, 2010). In our pilot studies (Tokatli et al., 2016; Webb et al., 2016) worked in pairs within the same virtual world, a decision which was largely dictated by the way the technology was set up (see Figure 1). In this set up one student navigates through the virtual world of a cell using a haptic device and stereoscopic 3D provided through the Oculus Rift headset while the other student views the cell on a standard computer screen and reads the lab script/worksheet. This arrangement provides for different roles of the two students.

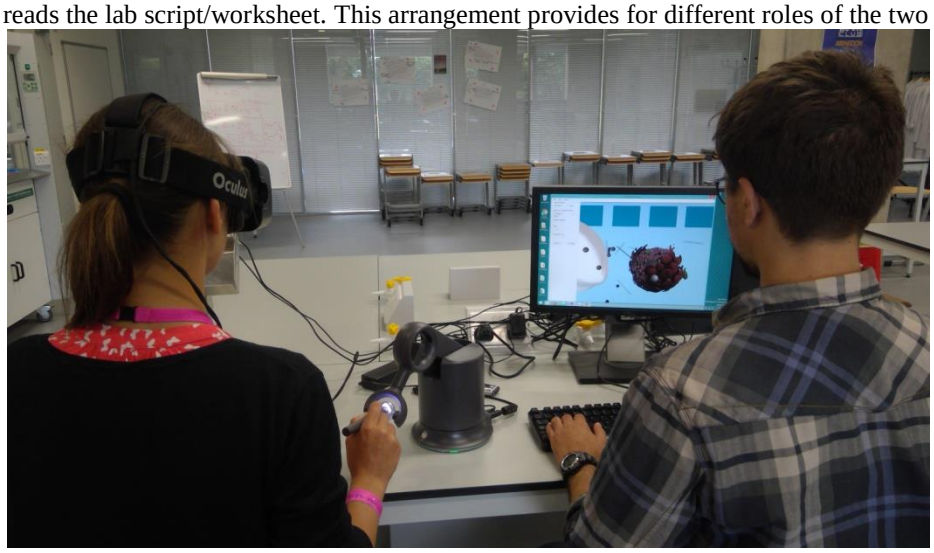

Figure 1 The setup used for a pilot study where students collaborated in pairs

One form of learning collaboratively in pairs, in a computer-based environment, that also emphasises the importance of clear roles is "pair programming". A review by Preston (2005) identified that pair programming is generally consistent with the attributes of collaborative learning. A key feature of the pedagogy of pair programming is that one student is the pilot and writes the program while the other is the navigator who reviews the task requirements and what is being typed and considers the progress at a different level of abstraction. In one of our pilot studies (Webb et al., 2016) we initially used the terms pilot and navigator for these distinct roles. However as the study proceeded, the term navigator appeared to be unhelpful and we changed the terms to pilot and co-pilot. The role descriptions seemed to be important in the way the students perceived the task: pilot and co-pilot emphasised their shared role in navigating the space and undertaking the task but with slightly different views and software capabilities. These findings were consistent with Bryant, S., Romero, P., & du Boulay (2008) critique of role descriptions in "pair programming where they suggested that the roles should be much more equal and the focus on encouraging productive talk. In our pilot study the tasks and questions were designed to encourage talk as well as requiring the students to work together making use of their different access and functionalities in their roles.

Modelling Cell Systems

Many simulations of cells are available both for education/training purposes and for cell biologists to use in their work. Creating models of cell organisation directly from static and moving images is an area of active research where the advantages of generative rather than descriptive models have recently been emphasised (Murphy, 2016 (in press)) and online open source software is available (http://cellorganizer.org/). When scientists have access to accurate models of cells they can use them for many purposes including simulating the effects of drugs etc. (Murphy, 2016 (in press)). Such models are likely to be too complex for cell biology courses in secondary school but the analysis by Murphy (2016 (in press)) outlines relevant design considerations that also apply to descriptive models and may be important for learning even in introductory courses. Specific considerations include the: relative size and spatial distribution of organelles in relation to each other; the movements of the components and the range of variation of size and shape in cells (even of the same type) and their organelles. Typically this modeling involves developing and combining a range of models and the complexity of cells means that many different possible models can be created. Here we are concerned with identifying the models and the level of detail that will be most useful for developing understanding for secondary school students. As noted previously in this paper, representations of scale in both standard textbooks and virtual resources are very unrealistic (de Oliveira & Galembeck, 2016) and may lead

to misconceptions. In our pilot study (Webb et al., 2016) we used a basic cell model adapted to work with a haptic device (see Figure 1). This stylised cell model, designed for educational use, was not realistically scaled but was intended to convey the typical characteristics of the organelles and as such it did support a discussion of the 3D arrangement of the organelles and their functions in protein synthesis with A-level students.

Learning activities in the virtual world

As explained earlier, learning activities need to be designed to support learning of specific objectives and to encourage students to connect their knowledge together (Tibell & Rundgren, 2010). In our pilot study (Webb et al., 2016), in order to support the students in relating their explorations in the virtual world to their broader understanding we started from a view of a sheet of cells (part of a tissue) and then enabled them to change views and "jump" to a much higher magnification. The learning activities were focused on revising the structure and functions of organelles involved in protein synthesis as these A-level students had already been taught this material. In our next round of prototyping we aim to work with GCSE students aged 14-16 and to develop activities to examine membrane transport in addition to the structure and function of cell organelles. Membrane transport has always been an important aspect of high school biology that presents learning and teaching difficulties (Friedler, Amir, & Tamir, 1987; Oztas, 2014; Tibell & Rundgren, 2010). Recently GCSE syllabuses have even become slightly more demanding in respect of these topics. The current AQA GCSE specification requires understanding of: partially permeable membrane, osmosis, diffusion and active transport and recommended activities include: "computer simulations to model the relative size of different cells, organelles and molecules; computer simulations to model the process of diffusion" (AQA GCSE specification 2014 onwards page 40). Activities to develop this understanding will require a further jump in magnification in order to enable interaction with the cell membrane and molecules that are transported across it in various ways. A design challenge is to represent the dynamic nature of the membrane components. While the overall membrane structure as a boundary remains relatively stable except during cell division, the molecules are in dynamic motion e.g. lipids in the main boundary layer exchange rapidly (every 10-100 ns) with other membrane lipids (Nicolson, 2014).

In the view of the project team an activity designed to be used with haptic devices and stereoscopic 3D interaction is likely to be one of a number of other classroom activities involving a range of different resources. Although we expect that developments in the gaming industry will ensure that haptic-interfaces as well as more advanced 3D stereoscopic display systems become commonplace and cheaper, such devices are still likely to be in short supply and also require some space in the classroom. Thus the haptic-enabled activity should involve a procedure which is significantly enhanced by the haptic interaction, e.g. feeling the forces on molecules in proximity to a cell membrane. Therefore in designing activities we need to take account of the range of typical activities that normally take place in biology lessons and find ways of linking between these activities in order to support development of a broader understanding and linking of different aspects of biological knowledge (Tibell & Rundgren, 2010). For example an introduction to cell biology in secondary school often involves students preparing microscope slides of their own cells from the lining of their cheeks. Therefore the virtual learning environment might build on this by taking the view that students have seen through a light microscope as the starting point and enabling them to explore within a virtual epithelial cell. Other activities might involve using specific mobile-based simulations or Internet searches to answer specific questions and then applying this knowledge with a 3D virtual world to solve a particular problem.

Conclusions

In this paper we have outlined ways in which we are addressing some of the design challenges in developing a haptic-enabled 3D virtual environment learning in school cell biology. We have outlined key issues in understanding cell biology that have been researched over many years as well as some of the more recent evidence of how TEL can support learning and teaching. Our current prototyping effort is focused on adapting a cell model to provide haptic-enabled interaction to support learning of membrane structure and function. In summary, in designing learning activities we need to take account of: curriculum requirements; cognitive challenges and specific difficulties in understanding that have been identified from the literature including integrating new understanding into existing knowledge and linking between different areas of knowledge biology and supporting understanding of relative sizes and scale; supporting students in developing their visual literacy and skills in using the haptic interface and navigating the 3D space; ways of encouraging/scaffolding students to learn collaboratively by designating roles and promoting relevant talk as well as considering how the haptic enabled activities can be integrated into lessons. The paper has focused on opportunities for addressing difficulties in learning in cell biology but many of the issues identified will apply to other areas of learning especially in biology and chemistry.

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