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An Investigation of the Impact of Haptics for Promoting Understanding of Difficult Concepts in Cell Biology

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Abstract. This paper reports on a study which investigated whether the addition of haptics (virtual touch) to a three-dimensional (3D) virtual reality (VR) simulation promotes learning of key concepts in biology for students aged 12 to 13 years. We developed a virtual model of a section of the cell membrane and a haptic-enabled interface that allows students to interact with the model and to manipulate objects in the model. Students, in two schools in England, worked collaboratively on activities, in pairs, designed to support learning of key difficult concepts. These concepts included the dynamic nature of the cell membrane, passive diffusion and facilitated diffusion. Findings from observation of the activities and student interviews revealed that students were very positive about using the system and believed that being able to feel structures and movements within the model assisted their learning. Results of pre- and post-tests of conceptual knowledge showed significant knowledge gains but there were no significant differences between the haptic and non-haptic condition.

Keywords. Haptics, virtual reality, cell biology, science learning

1 Introduction and background

Haptics provides the additional sense of touch to a virtual reality (VR) environment, thus enabling people to feel the objects they are interacting with. Furthermore, a haptic-enabled interface can enable people to directly manipulate objects in a three-dimensional (3D) VR environment much more realistically than is possible through more standard interfaces such as mouse and tracker ball. Our research objectives were to: 1) design and develop a haptic-enabled VR environment that would enable students to explore difficult concepts through multisensory collaborative activities; 2) investigate whether or not the ability to feel the interactions through touch affected students' development of understanding of key concepts; and 3) examine students' perspectives on the interactive learning experience.

We focused on cell biology as an important area of science learning that poses significant challenges that may be addressed through the use of VR simulations.

Understanding cell biology is critical for understanding biology as a whole [1], but introductory courses tend to be limited in their scope, mainly owing to the difficulties of developing conceptual understanding of such complex systems that cannot be observed directly. Furthermore, there is evidence that persistent misconceptions are common in cell biology at school level [2, 3].

The model developed for this study was of a section of the plasma membrane, otherwise known as the cell membrane, which is the membrane surrounding all cells. The decision to focus the study on cell membrane structure and function was based on three main considerations: 1) the crucial importance of cell membranes for the overall understanding of biology; 2) the prevalence of conceptual difficulties and misconceptions in learning about membrane structure and function; and 3) the good opportunities for haptic exploration of the forces at work in membrane transport. The way in which the cell membrane controls movement of materials into and out of cells, through diffusion, active transport, facilitated diffusion, etc., is critical for the functioning of biochemical processes. Known problems in understanding these particular phenomena include: a persistent anthropomorphic view of processes and assignment of intentionality to cell functions [2]; issues in understanding magnification and scaling [4]; problems in understanding randomness in relation to diffusion [5]; and issues in visualisation of cell structures with different representations [6]. Specific misconceptions that have been identified previously include: molecules diffuse depending on the space available [7]; diffusion in a cell depends on the “living” processes of the cell and therefore stops following the death of the cell [8]; and a substance dissolved in a liquid spreads out by breaking into smaller particles.

Haptic interaction in a VR simulation can enable students to experience forces resulting from concentration gradients, suction effects of specific carrier proteins as well as to feel the virtual representations of microscopic structures whose shape is critical for their function. Thus, we have chosen to investigate a learning situation where haptic interaction may be particularly beneficial.

Previously, Webb et al. [9] argued that the potential benefits for learning science concepts, of the addition of haptics to a VR simulation, derive from: 1) the known general benefits of multisensory learning compared with uni-sensory; 2) engagement and motivational effects of a more realistic experience; and 3) the more specific possibility that haptic interaction will support the visualisation that is necessary for understanding many key processes in science [10]. A possible theoretical foundation for the suggested improved learning associated with haptic support for visualisation comes from Dual Coding Theory [11, 12] which proposes that distinct interconnected systems for different sensory modalities act synergistically.

In this paper, we first discuss the principles and design of the VR environment that we developed for this study, and the haptic-enabled interface designed to explore the VR environment. We then discuss the nature of the interactive learning environment and activities that we developed, based on findings from previous studies [9]. The methods for collecting data, preliminary results and discussion of findings then follow.

2 Design of the VR environment

Designing the VR environment presented several challenges. First, cell membranes and the ways in which they control the movement of substances into and out of cells are very complex, so achieving a realistic model, for example by using real images, was impossible. Therefore, it was necessary to identify suitable iconic ways of representing structure and function. Understanding cell membrane function is crucial for understanding both the normal functioning of cell and organ systems as well as the opportunities for bio-engineering, and is an area of active research [see, for example, 13]. However, determining what level of understanding of such complex systems would be desirable and achievable for the target group of students presented a challenge. Furthermore, understanding of the functioning of cell membranes is an area of cell biology that leads to significant student comprehension problems and misconceptions, as explained earlier [2, 14]. It is likely that some of these problems and misconceptions result from poor models and representations currently used for teaching. Therefore, key considerations for the design of the model included:

1. Identifying a level of complexity that would be sufficiently accurate not to lead to misconceptions, while being feasible to be modelled in a virtual environment and not too complex for students aged 12 to 13 years to understand.
2. Deciding on the level of detail for representing molecular structures that would enable understanding of their function in membrane transport.
3. Representing the relative size and scale of structures within a confined space, given that manipulation of the haptic-enabled interface is restricted to a limited vertical and horizontal space.
4. Modelling the haptic forces in such a way that students would be able to feel forces and manipulate the structures.

The screenshot in Figure 1 shows the cell membrane model near the start of the activity. The phospholipid bilayer of the membrane is depicted as a straw-coloured barrier with some hexagonal shapes representing the idea that the layer consists of many separate molecules and the bilayer is also indicated by the cross-sectional view. However, the details of the bilayer were not considered to be important for students aged 12 to 13 years to understand. The pale cream structures penetrating through the membrane represent the membrane proteins; several different types of membrane protein were modelled. Carbon dioxide and oxygen molecules, represented by their coloured atoms, following the CPK (Corey, Pauling, Koltun) colouring convention, can be seen in Figure 1.

The user is able to interact with the system via two points of contact of the thumb and index finger on the same hand (either left or right) by means of a thimble device as shown in Figure 2. In the model, the fingers are able to move freely through the cell membrane but when the user grabs hold of an object in the model, such as a glucose molecule, if the haptics is enabled, the user feels the object and any forces acting on that object, such as those resulting from concentration gradients. In the non-haptic condition, the user interacts using the same interface, but the haptics is turned off in the software, so the user must rely on visual cues to grab objects. When the user makes contact with one of the substances, the “Label” changes to show the name of the

substance (carbon dioxide, oxygen, glucose, sodium and potassium). When haptics is enabled, users can feel forces on the substances, depending on their concentration, as they push a molecule or ion. During the simulation, users can add more molecules and ions, thus changing the concentration gradient. Some of the membrane proteins are modelled as glucose transporters, based on the GLUT1 transporter, as far as its structure and function is known [15]. When a user pushes a glucose molecule towards a glucose transporter, the user feels the force as the molecule is drawn into the transporter protein, and the model simulates the glucose transporter changing shape as it transports the glucose molecule through the membrane.

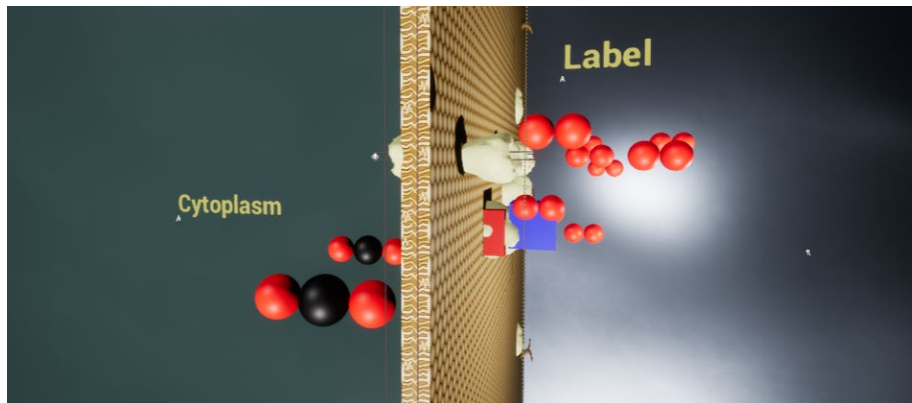


Figure 1. View of part of the cell membrane model

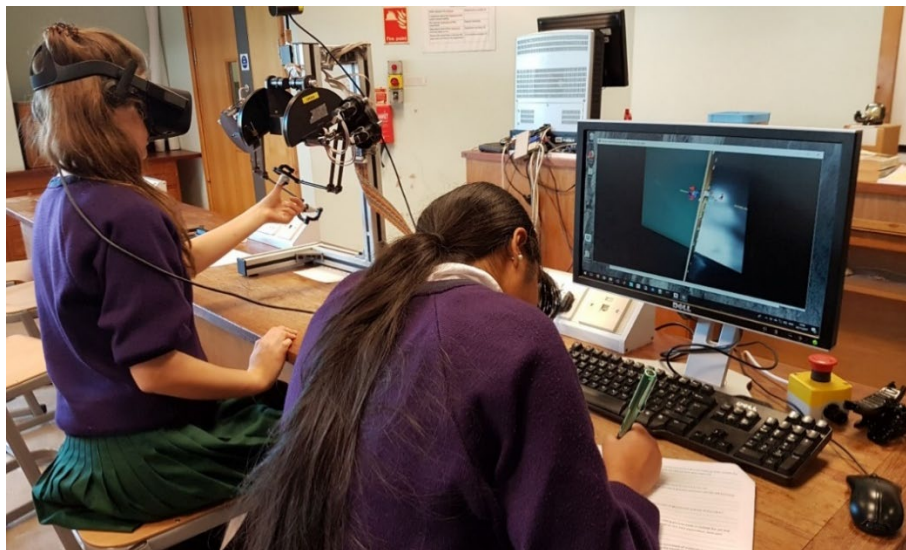


Figure 2. Students using the system

3 The interactive learning environment and activities

As shown in Figure 2, students worked in pairs, where one student (the pilot) was immersed in the VR environment using the interface and the head-mounted display, while the other student (co-pilot) had the same view of the 3D environment on a standard computer screen. The pilot controlled the interaction with the VR environment while the co-pilot directed the activity by: reading the instructions and questions on the worksheet; controlling some aspects of the model through the keyboard; and writing the answers onto the worksheet. The design of this learning environment was informed by a series of investigations with previous prototypes and discussions with teachers and students [9]. The following were the main design principles:

1. to focus students' attention on the haptic interaction and feel of the structures through the activities and questions;
2. to encourage students to learn collaboratively by discussing their ideas;
3. to encourage students to formulate their ideas precisely.

For the students, aged 12 to 13 years, who were the subjects in our study, their usual study of cell membranes included examination of cell preparations under the light microscope, where cell membranes appeared as a thin line stained with a dye, together with two-dimensional diagrammatic representations and teaching and discussion regarding how membranes function to control movement into and out of cells, specifically through diffusion, osmosis and active transport.

Based on considerations of the existing curriculum, activities were designed to develop understanding of the following key concepts:

1. The cell membrane is a barrier to the movement of some substances whereas others pass through freely.
2. Substances move in the cellular fluid by diffusion and some substances are able to continue moving by diffusion through the membrane.
3. The movement of substances that are able to freely diffuse depends on their individual diffusion gradients.
4. The cell membrane is a dynamic structure in which membrane proteins "float".
5. Carrier proteins enable the movement of some substances through the membrane by attracting a specific molecule and changing shape as the molecule passes through the channel of the transporter.

4 Research methodology

The study was carried out in a boys' school and a girls' school with students who were in their first term of Year 8 (aged 12 to 13 years). Both schools were independent and selective, so the students were of relatively high academic ability. Opportunist sampling was used, based on which students could be freed from lessons at the time of the study. Pairs of students were assigned randomly to the haptic or non-haptic condition in equal numbers, and the students were not informed of this difference. In all, data were obtained from 32 pairs of students: 16 pairs in haptic-enabled condition, and 16 pairs in non-haptic condition.

In line with ethical considerations, the purpose of the study was explained carefully to the students, and theirs' as well as their parents' consent for the data collection was obtained. As some students were only exposed to the non-haptic condition, in a follow-up study later in the academic year, we ensured that all students had the opportunity to experience the haptic condition.

A test of biology knowledge, based on the key concepts listed above, and incorporating 14 true/false questions, was administered before and after the activity. While students were undertaking the activity (approximately 40 minutes in duration) they were video recorded. Students were observed by members of the research team who made notes on how students engaged with the activities and with each other. The research team later reviewed the notes and videos in order to identify advantages and limitations of the system and interaction. Students worked through the activity using the worksheet without teacher support; technicians were on hand to deal with technical issues with the hardware and software. Following the activity, students were interviewed in pairs using a semi-structured interview of about 20 minutes duration that elicited students' perspectives on: using the VR system; carrying out the activities; and collaborating while using the VR system as well as their thoughts on their learning during activities. The interviews were transcribed and subjected to inductive coding and thematic analysis. In this paper, we focus on the value of haptics for learning by examining both students' knowledge gains and their perspectives on their learning and how learning may be supported by the activities and the system.

5 Results

Observations of students during activities showed that both those in the haptic and non-haptic condition were engaged with the tasks and most pairs worked very well together to support each other in interacting with the system and answering the questions. The majority of the students had not previously used VR systems and therefore the experience was novel and exciting. Generally, students quickly became familiar with the system and were able to use it effectively. There were some technical problems, particularly with the thimble devices, so it was sometimes necessary to stop and restart the system in order to adjust the thimble devices. The technical problems were quickly resolved by technicians or the students themselves and generally did not interfere with the progress of activities.

Table 1. Comparison of pre- and post-test results for the true/false questions

	Condition	Mean	Standard Deviation	N
Pre-test Score	Haptic	5.5000	2.03200	32
	Non-Haptic	4.8438	2.15690	32
	Total	5.1719	2.10483	64
Post-test Score	Haptic	8.3125	1.97464	32
	Non-Haptic	8.3437	1.42805	32
	Total	8.3281	1.70949	64

Table 1 shows the scores for the 14 true/false questions on the knowledge tests. There was no significant difference in the pre-test scores for haptic (M=5.50, SD= 2.03) and non-haptic (M=4.84, SD=2.16) conditions; $t(62)=1.25$, $p=.22$. There was also no significant difference in the post-test scores for haptic (M=8.31, SD=1.97) and non-haptic (M=8.34, SD=1.43) conditions; $t(62)=-.07$, $p=.94$.

There was a significant difference ($p<0.001$) between the pre-and post-test results suggesting that students had improved their understanding by undertaking the activities. However, whether the participants were in the haptic or non-haptic condition did not affect the change in score ($p= 0.23$). While the overall scores on the test improved, incorrect answers remained, including, particularly, answers related to Key Concepts 3 and 4 (see Section 3).

All the pairs of students reported that they found the system generally easy to use. However, a significant minority of pairs, both in haptic and non-haptic conditions, said that they found difficulty in grasping the objects in the system. Nearly all the students reported that they enjoyed working in pairs in these activities and found learning collaboratively was well supported by the system.

All the students who experienced the haptic-enabled condition were positive about being able to feel the particles. They commented particularly that they believed they gained a better understanding through using the VR system and specifically through being able to feel, especially compared with more traditional methods of teaching and learning such as listening to the teacher or viewing static diagrams. For example, when asked what they liked about the system, one student commented: *“I liked the touch about it, so I’d know what it feels like”* and further when asked about the benefits for their learning: *“Well, because if you looking at it you can only imagine what it’s like, so you don’t actually know what’s it’s like for real”*

Students who worked in the “non-haptic” condition were also positive about the system and valued the visual experience but also commented on the value of being able to grasp and move the objects. The students were not told that the haptics had been disabled and were asked the same questions as the experimental group, including questions about the feel of the model, e.g. in the interview they were asked: “do you think being able to feel the membrane and the particles virtually can help you learn better, and why?” Some of these students were well aware of the lack of feel and commented on this as a limitation of the system, e.g. *“It was hard ‘cause it kept asking the question how you feel, but I couldn’t physically feel so I didn’t actually understand what, like, the question...”* However, many of the students did not comment on this lack of feel. Some found the fact that they could grasp objects with their fingers but not feel them quite strange, e.g. *“We couldn’t actually feel them in a way... It’s really weird, it’s like you can see you’re moving something but you can’t feel like actually sense that you’re moving it.”* Others thought that they were somehow compensating by imagining the “feeling” of what they were seeing, e.g.:

“I didn’t feel too much, actually, with the haptic feedback... But, I think it really will improve kind of being able to feel the resistance, cos you can kind of feel it in what you’re seeing. But there probably just needs to be a bit more actual vibrations, for example, coming out of the system” (Student in non-haptic condition).

Overall, the students felt that being able to interact with a haptic-enabled VR system would support their learning.

6 Discussion and conclusion

Findings from the interviews, together with observations of the activities and videos, showed that the students: were engaged with the system; they worked well together in pairs to complete the tasks; enjoyed the activities; found the experience fun and interesting; and believed that they were learning. Furthermore, findings from the pre- and post-tests revealed that students had better understanding of the subject matter after undertaking the activities with the system. Therefore, we can conclude that the design of the model and interface and the associated activities were: suitable for the students; enabled collaboration; were engaging and motivating; and supported students in learning most of the key concepts.

Observations of the students while they were undertaking the activities as well as students' own perspectives revealed that turning off the haptic feedback generally did not inhibit the students from interacting with the system and carrying out the activities. We can therefore conclude that students were able to compensate for the lack of feel through visual cues. As there was no significant difference in knowledge gains between the haptic and non-haptic condition in this study, turning off the haptics so that students could not actually feel the objects appears not to have affected their learning of concepts. This finding needs to be interpreted with caution. It is possible that just being able to grab the objects with their fingers enabled students to explore the environment and hence to learn. However, it is also noteworthy that on the post-test, students still found difficulty with some concepts that we had expected would be supported by their experiences of haptic feedback. Some observations during activities suggested that students were not experiencing the full effects of the haptic feedback that we had expected. This may have been because they had difficulties grasping objects, owing to problems with the thimble interface. Alternatively, or in addition, the forces may not have been sufficiently strong for students to notice. A possibility is that the students did not notice haptic stimuli because the visual stimuli, which were novel and exciting, directed their attention away from the haptic stimuli. "Visual dominance" is a well-known psychological phenomenon, which suggests that people are more likely to notice and respond to visual stimuli than those from their other senses. For example, even in experiments where participants were compelled to attend to a particular sensory stimulus, an irrelevant visual stimulus interfered much more with their response to an auditory stimulus than vice versa [16]. Lukas et al. explained these findings in relation to the theory of directed attention [17], which claims that visual stimuli are not as automatically attention-capturing stimuli as other modalities, so people have to actively focus their attention towards visual stimuli, which therefore occupy more of their attentional resources. A recent review [18] revealed that a majority of studies suggest that attentional resources are distinct for visual and auditory sensory modalities. However, findings vary, and may be dependent on the type of response being investigated and the context of the study. In this review, consistent with the majority of recent studies, the emphasis was on visual and auditory rather than haptic. Furthermore, the studies included in their review were focused in the real world whereas there is evidence that people's perceptions of touch vary between the real world and other representations. For example, Gaffary et al. [19] found, in an experimental study, that people's perceptions of a virtual piston differed between an augmented reality (AR) and VR environment. A recent review also shows that there are variations in

multisensory perception with age and across different groups [20]. In summary, although we kept the other conditions of the investigation basically the same between the experimental and control groups, the interactions between students and the VR environment and between students in their pairs, provided many opportunities for variations that may have influenced learning. In further research, we will be conducting video analysis of the interactions and undertaking further experiments in order to examine these possibilities in depth.

Whether or not the haptic feedback is critical for students' learning, the addition of haptics to a VR system does provide a more complete and authentic experience. Furthermore, some students found the experience of being able to grasp objects without feeling them to be strange. Currently, the addition of haptics to VR systems presents significant technical challenges. Therefore, typically VR systems rely heavily on visual representation and haptics is generally lagging behind the visual in implementation, including in, for example, surgical applications, where there is evidence that incorporating haptic feedback would be valuable [21]. Currently, haptic interfaces are relatively expensive, whereas the costs of VR systems with 3D visual interfaces are reducing. If, as expected, it becomes possible to provide relatively inexpensive haptic interfaces to VR systems, then it will be important to identify the relative learning benefits and issues associated with haptic feedback in various situations.

While this investigation was of necessity conducted outside of their normal lessons and no elements of the usual interaction with a teacher were included in the activities, it is expected that similar activities could be incorporated into normal classroom lessons. For example, a haptic activity might be incorporated into a circus of investigations, in which students move around from one activity to the next during a lesson. Such activities might include various investigations using VR and haptics as well as the standard laboratory cell studies.

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