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James Minogue [a]; Gail Jones [a]
[a] North Carolina State University, Raleigh, North Carolina, USA

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RESEARCH REPORT

Measuring the Impact of Haptic Feedback Using the SOLO Taxonomy

James Minogue* and Gail Jones
North Carolina State University, Raleigh, North Carolina, USA

The application of Biggs' and Collis' Structure of Observed Learning Outcomes taxonomy in the evaluation of student learning about cell membrane transport via a computer-based learning environment is described in this study. Pre-test–post-test comparisons of student outcome data (n = 80) were made across two groups of randomly assigned students: one that received visual and haptic feedback, and one that relied on visual feedback only as they completed their virtual investigations. The results of the Mann–Whitney U-test indicated that the group mean difference scores were significantly different statistically (p = .043). Practically speaking, this study provides some early evidence suggesting that the haptic augmentation of computer-based science instruction may lead to a deeper level of processing. The strengths and weaknesses of this current diagnostic approach and a novel approach based on a non-verbal model of cognition are discussed in light of their potential contributions to the teaching and learning of science.

Introduction

It has become generally accepted that advances in computer technologies are impacting teachers' instruction and students' learning about science concepts and phenomena. Many researchers (e.g., Bransford, Brown, & Cocking, 1999; Dilek & Akaygun, 2004; Linn, 2003; Smetana & Bell, 2006; White, 1992) suggest that the use of computer-generated simulations and microworlds can be ideal vehicles for promoting the active engagement of school-age children in the learning of complex science content. Moreover, it is now possible to add haptics (simulated tactile and kinesthetic feedback) to computer-based learning environments, extending and potentially enhancing the users' ability to interact with virtual objects and events. However, there is less of a consensus as to how to assess accurately the efficacy of these technologies. Today educational researchers are finding it increasingly difficult

*Corresponding author. Department of Elementary Education, North Carolina State University, Campus Box 7801, Raleigh, NC, 27695-7801, USA. Email: james_minogue@ncsu.edu

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to measure student learning accurately in these rapidly evolving computer-based learning environments.

The goal of this study is two-fold. One primary aim is to examine the utility of Biggs' and Collis' (1982) Structure of Observed Learning Outcomes (SOLO) taxonomy as a means to assess student learning about cell membrane transport via a computer-based instructional programme. We also explore this particular diagnostic tool's ability to detect differences in understandings resulting from the addition of haptic feedback.

Results of this exploratory work, as well as the strengths and weaknesses of the analytic approach (as we see it), are discussed. This model of assessment may prove to be a valuable tool for measuring the cognitive impact of computer-based teaching tools. In turn, further refinement and use of this diagnostic approach may help researchers gather much needed empirical data that can be used to support or refute the numerous philosophical and theoretical claims being made about the pedagogical power of innovative computer-based tools in the teaching of school science.

Review of the Related Literature

The literature that is germane to this study is drawn from three primary areas: the origin and application of the SOLO taxonomy, students' understandings of the cell, and haptic perception and technology. Each will be detailed in turn below.

The SOLO Taxonomy

The SOLO taxonomy, developed by Biggs and Collis (1982), provides educators and researchers with a systematic way of classifying and describing the range of performances produced by learners in attempting a particular academic activity such as writing an essay or answering an open-ended question. It was informed by, and extends, Piaget's stages of development and it can be used to analyse the structure of children's understandings. Biggs and Collis built their model on the notion that in any 'learning episode, both qualitative and quantitative learning outcomes are determined by a complex interaction between teaching procedures and student characteristics' (1982, p. 15). This can be taken to mean that students' prior knowledge regarding the content, the students' motives and intentions about the learning, and the students' thinking strategies all impact what is ultimately learned.

The SOLO model describes five levels of sophistication: Prestructural, Unistructural, Multistructural, Relational, and Extended Abstract. These levels are ordered in terms of various characteristics, including the movement from the concrete to the abstract, the use of an increasing number of organising aspects, increasing consistency, and the relating and extending of key principles (Biggs, 1999; Biggs & Collis, 1982).

According to this assessment system, *Prestructural* responses indicate no understanding. The two 'surface level' responses (*Unistructural* and *Multistructural*) suggest an understanding of ideas or facts. *Unistructural* responses are characterised by the use of only one piece of information, fact, or idea, obtained directly from the problem. With an increase in quantity, *Multistructural* responses make use of more than one piece of information, fact, or idea. Still each piece of information is treated separately with no integration of the ideas.

In contrast, the two 'deep level' responses (*Relational* and *Extended Abstract*) suggest a change in the quality of responses; they are, in essence, cognitively more robust. *Relational* responses integrate of at least two separate pieces of information, facts, or ideas, which working together answer the question. Responses that lie in the highest level of the SOLO taxonomy (*Extended Abstract*) go beyond the given information, knowledge, or ideas, and deduce a more general rule or proof that applies to other scenarios. These responses can be sighted as evidence of 'transfer'. Table 1 more fully describes the various levels of the SOLO taxonomy.

It has been suggested that one of the strengths to this analytic approach lies in its generality; that it is not content dependent. As such, this model has been employed to assess student learning in a variety of subject areas, including poetry (Biggs & Collis, 1982), history (Biggs & Collis, 1982), mathematics (Collis & Romberg, 1992), geography (Courtney, 1986), and science (Collis & Davey, 1986).

However, we speculate that the SOLO taxonomy will be particularly useful in determining whether the additional sensory information afforded by haptic technology impacts the manner in which students' come to understand complex objects and events. There have been numerous theoretical claims made about the pedagogical power of haptic feedback (e.g., Loucks-Horsley et al., 1990; Okamura, Richard, & Cutkosky, 2002; Reiner, 1999; Wadsworth, 1989; Williams, Chen, & Seaton, 2003). These assertions all point to the construction of a more complete, a more connected, and a deeper understanding due to the addition of touch. Although the SOLO taxonomy was not intentionally designed to assess the influence of sensory feedback and/or manual interactions, we assert that this tool's inherent attention to the respondents' ability (or inability) to connect and relate facts into a coherent whole will make it well suited for the accurate assessment of impact of haptic feedback.

Table 1. SOLO taxonomy used in the analysis of student responses

Level		Description
1	*Prestructural*	The task is not attacked appropriately, the student has not understood the point, or question is reworded.
2	*Unistructural*	One aspect of the task is picked up and used (understanding as nominal).
3	*Multistructural*	Several (two or more) aspects of the task are learned but are treated separately (understanding as knowing about).
4	*Relational*	The components are integrated into a coherent whole, with each part contributing to the overall meaning (understanding as appreciating relationships).
5	*Extended Abstract*	The integrated whole at the relational level is reconceptualised at a higher level of abstraction, which enables generalisation to a new topic or area, or is turned reflexively on oneself (understanding as far transfer and as involving metacognition).

Students' Understandings of the Cell

There has been a considerable amount of research conducted with individuals spanning the educational sequence that has investigated and described what students know about the structure and functioning of cells (e.g., Dreyfus & Jungwirth, 1989; Flores & Tovar, 2003; Marek, 1986; Tamir & Zohar, 1991; Westbrook & Marek, 1991). Viewed collectively, the results of this work suggest that the majority of learners find these topics difficult to conceptualise meaningfully. More specifically, it has been found that students' hold an anthropomorphic view of cell processes (Tamir & Zohar, 1991). Notions like: the cell *knows* what to take in and what to discard dominate the thinking of many students (Dreyfus & Jungwirth, 1989). Prior research also suggests that many students have difficulty understanding that the cell is able to carry out the basic processes necessary for life as an autonomous organism. Further, the establishment of relationships between cell structures and their functions are especially complex for students who are not able to *integrate* them into an overall picture of the cell (Flores & Tovar, 2003). Yet another issue is students' apparent difficulty in conceptualising the relative and metric sizes of cells, which often results in confusion between cells, atoms and molecules that has been shown to interfere with students' ability to develop a robust understanding of other fundamental biological processes such as diffusion (Westbrook & Marek, 1991).

Despite the fact that diffusion is experienced in everyday life and is easily demonstrable in a classroom, a clear understanding of the process seems to elude many school-age students. It is a process that crosses the disciplinary boundaries of chemistry and biology, which in itself seems to exacerbate students' conceptual difficulties. This difficulty may also arise from the need to visualise the molecular events that govern the process. This work (e.g., Marek, 1986; Odom, 1995; Westbrook & Marek, 1991) has been conducted with individuals that span the educational sequence and suggest that the majority of learners find these topics difficult to construct meaningful understandings of.

Again, the study reported here is exploratory in nature, and while there is very little research that has directly investigated the efficacy of haptic feedback as a means to address students' difficulties in learning about cellular structure and functioning, there is surface logic in the application of haptics technology in this context. More specifically, active touch involves intentional actions that an individual chooses to make. Sathian (1998) has suggested that involving students in consciously choosing to investigate the properties of an object is a powerful motivator and increases attention to learning. This increase in attention may impact what and how students select information for processing.

Haptic Perception and Technology

Of the five sensory channels—sight, sound, taste, smell, and touch—it is only our sense of touch that enables us to modify and manipulate the world around us (Kennedy, Gabias, & Heller, 1992). We commonly use touch to discover the world around us, and information gained through touch lays the foundation for the development of a wide range of concepts but, despite its perceptual power and the wealth of sensory information it affords us, the sense of touch has emerged as an understudied and perhaps under-utilised teaching tool. Additionally, there is evidence that touch is a fully cognitive system providing the basis for conscious memory and learning (e.g., Brooks, Ouh-Young, Batter, & Kilpatrick, 1990; Florence, Gentaz, Pascale, & Sprenger-Charolles, 2004; Klatzky & Lederman, 2002; Loomis & Lederman, 1986; Reiner, 1999).

The relatively recent addition of touch in computing has made it possible to extend students' interactions in computer-based learning environments. Current haptic devices, providing simulated tactile and/or kinesthetic feedback, enable users to not only see but also 'feel' and manipulate three-dimensional virtual objects (McLaughlin, Hespanha, & Sukhatme, 2002). Available haptic devices vary in sophistication and fidelity. At one end of the spectrum lie vibrating game pads and force-feedback gaming joysticks, which offer limited interactivity. These devices churn out rather crude haptic effects usually via open loop feedback and/or predefined feedback signals. At the other end of the continuum reside the sophisticated 'laboratory-grade' haptic devices. These apparatuses seamlessly marry complicated software and intricate hardware to provide the user with a high level of interactivity and fine-grained sensory clues. Naturally, the cost of haptic devices mirrors this range in capabilities. The high-end tools used by haptics researchers have been grouped into two broad categories: data gloves and point-probe devices (Burdea, 1996; Hayward, Oliver, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004). Although other types of haptic feedback devices exist (e.g., tension-based and vibrotactile), these devices represent the bulk of what is presently sold and used.

These technological advances have spawned the development of haptically augmented immersive learning environments that are being used in the training of military and medical personnel, as well as the teaching of students but to a much lesser degree. Research from experimental psychology and neuroscience has shown that vision dominates in the perception of macrogeometry (shape) and colour (Sathian, Zangaladze, Hoffman, & Grafton, 1997). Conversely, it has been demonstrated that haptics is superior in the perception of substance or microspatial properties such as texture, compliance, elasticity, and viscosity (Lederman, 1983; Zangaladze, Epstein, Grafton, & Sathian, 1999).

What is not well known is how the addition of haptic feedback impacts the way in which individuals integrate this information during the 'meaning-making' process. The bulk of the research on human haptic perception report on studies conducted with subjects deprived of vision exploring actual objects with whole hands in controlled settings (e.g., Klatzky & Lederman, 1999; Lederman & Klatzky, 1987, 1990). This has made the exploration of how sighted individuals learn when they are remotely exploring computer-generated objects or events using the rigid point-probe of a haptic device thorny. To date, there have been only been a handful of studies (e.g., Jones, Andre, Superfine & Taylor, 2003; Minogue, Jones, Broadwell & Oppewal, 2006; Florence et al., 2004; Reiner, 1999; Williams et al., 2003) that have directly and systematically explored this line of inquiry. As suggested at the onset, the accurate assessment of student learning in these immersive three-dimensional environments has been especially challenging. Perhaps our application of the SOLO taxonomy will begin to shed light on this issue.

Methodology

Study Design

This study was part of a larger series of investigations that examined the efficacy of the haptic augmentation of a computer-mediated instructional programme on middle school students' understandings of cell concepts (Minogue et al., 2006). The focus of this particular analysis was to examine how haptic feedback influenced students' understandings of passive transport through the cell membrane. To fully understand this relatively complex process, the learner must be able to join together several critical pieces of information. Namely, the structure of the phospholipid bi-layer, the role of integral proteins, the influence of particle size, shape, and chemical charge, as well as the concept of equilibrium must be integrated into a complete and coherent construct of passive transport. We felt that this fundamental biological concept was conceptually rich and appropriate for the application of the SOLO taxonomy. We hypothesised that the SOLO taxonomy would present itself as a viable way to measure whether these cognitive demands were managed effectively by the student participants.

The research was conducted at an urban middle school in the South Eastern USA that served predominately low income (68% qualify for free or reduced lunch) students. The participants (n = 80) were drawn from four of the 12 intact seventh-grade integrated science classes. This sample was comprised of 37 females and 43 males with an ethnic composition of 5% Asian, 18% Caucasian, 19% Hispanic, and 58% African American.

The study employed a randomised pre-test–post-test control group design. Participating students were randomly assigned to either the experimental or control group (n = 40 each). The two treatment groups are described in more detail in the section that follows. Both groups experienced the same core computer-mediated instructional programme, Cell Exploration (also described further below). Students in the experimental group received bi-modal (Visual + Haptic) feedback as they completed the programme. Conversely, members of the control group only received uni-modal (Visual) information as they worked through the computer-mediated activity.

The Instructional Programme

The Cell Exploration programme, shown in Figure 1, simulated the structure and function of the cell membrane as it pertains to the process of passive transport and the mechanisms behind the membrane's selective permeability. The instructional programme allowed students to 'grasp' the various molecules (water, oxygen, and glucose) and a potassium ion that were modelled and to attempt to pass them

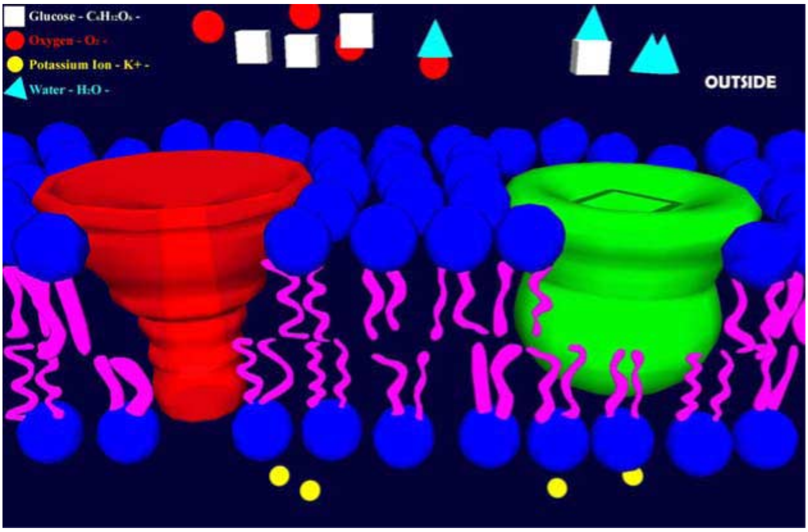

Figure 1. Screenshot of a portion of the Cell Exploration instructional programme

through the cell membrane. The aim of the programme was to have students discover that substances (depending upon the shape, size, and chemical charge) pass through membrane in different ways. Some substances can simply diffuse through the phospholipid bi-layer while others rely on the protein channels to facilitate the diffusion process. The students were challenged in a game-like scenario to move the substances in or out of the cell in order to reach equilibrium.

The software was designed to allow students to follow on-screen instructions that prompted them to explore the structure and function of a typical animal cell membrane in a semi-structured environment. Although the actual engagement time of the students was not recorded, student's progression through the programme was monitored by a researcher who followed a *Cell Exploration Guide* (see Appendix A). This guide served as a template for the researcher as he/she guided the students through the instructional programme. Script-like in nature, its purpose was to control for total time on task (30 min) and to help ensure that all students had a similar experience, attending to the same science content being presented. It is also important to note that there is no audio feedback provided during any portion of the instructional programme.

Treatment Groups

Students in the Visual + Haptic (V + H) experimental group received haptic feedback via a PHANToM® desktop device (Figure 2) as they conducted their investigations (SensAble, n.d.). This small, desk-grounded, robot-like arm permits simulation of fingertip contact with virtual objects through a pen-like stylus. The device tracks the *x*, *y*, and *z* Cartesian coordinates and the pitch, roll, and yaw of the virtual point-probe as it moves about a three-dimensional workspace, and its actuators communicate

Figure 2. PHANToM® desktop device from SensAble Technologies, Inc (Woburn, MA, USA).

forces back to the user's hands and arm as it detects collisions with virtual objects, simulating the sense of touch (Salisbury, Brock, Massie, Swarup, & Zilles, 1995). Figure 3 illustrates the complete user interface including the PHANToM® desktop device and PC-based laptop.

This device afforded experimental group students' the ability to 'feel' modelled forces associated with the passive transport of the substances. For example, students in this group could 'feel' that the glucose molecule could not fit through the heads of the phospholipid bi-layer. Additionally, experimental group students could 'feel' the potassium ion being pulled through the protein channel and 'feel' how the glucose molecule fit into its protein channel, causing a conformational change in the protein.

Students in the control or comparison group (Visual group) used the identical computer interface (PHANToM® desktop device and laptop computer); however,

Figure 3. Depiction of the complete user interface

the haptic feedback was turned off during their exploration. As a result these students did manipulate (e.g., grab and move) the molecules and did experience a diluted motion component of haptic feedback. That is, they used the point-probe much like a traditional computer mouse. Students in this group did not sense any resistance or force feedback and thus primarily received visual stimuli.

Data Source and Analyses

Students' knowledge (pre-intervention and post-intervention) regarding the mechanisms underlying the passive transport of materials through the cell membrane was assessed through their written responses to an open-ended question that read 'The cell membrane is often described as a *selectively permeable barrier*. In your own words, explain what this means. Be as specific as possible in your explanation'. Again, we purposefully chose to focus our analysis on these responses because of the multifaceted nature of the problem. That is, to arrive at the scientifically accepted answer the learner must be able to comprehend and unite several key understandings (i.e., cell membrane structure, membrane function, and concentration gradients). It was anticipated that the open-ended nature of this prompt would elicit rich and descriptive explanations of this complex cellular function.

The SOLO taxonomy (discussed earlier in Review of the Related Literature) was used to code all of the students' written responses. Coding categories included *Prestructural* (lowest level), *Unistructural*, *Multistructural*, *Relational*, and *Extended Abstract* (highest level). These levels were considered ordinal and were assigned numbers ranging from 1 to 5. For instance, one student's pre-assessment response reading 'It (substances) gets in or out because the cell membrane moves around a lot' was coded as a 1 (*Prestructural*). This response does not show any evidence of understanding regarding the target concept.

Contrast this with a different student's answer: 'The cell membrane controls the movement in and out of the cell and it is probably one of the most important parts. Water and food has to get through the barrier in order to get into the vacuole'. This response was coded as a 3 (*Multistructural*) because two aspects of the cell membrane's function are noted (importance and selective permeability of the membrane) but not related and are integrated into a coherent whole conception of the membrane's functioning. Table 2 provides more examples of actual student responses organised according to the SOLO taxonomy level.

Two science education researchers randomly selected and independently scored 20 pre-test and 20 post-test responses to the above stated question; this constituted 25% of the total responses. Intercoder reliability, defined here as the percentage of coding agreements, was found to be 0.83. Coder disagreements were discussed in order to clarify and refine the application of this diagnostic tool, and then the remaining 120 responses were evaluated.

Once all responses were scored, students' pre-test level, post-test level, and difference scores (pre-test to post-test) were tabulated and the frequency distributions were determined. Next, a direct comparison of the difference scores across treatment

Table 2. Sample student responses

Level		Sample responses
1	*Prestructural*	'It means that it is a barrier that can bring anything in or out'; 'The membrane controls the cell'; 'I don't know'
2	*Unistructural*	'It is how big it is because some small ones can get in and big ones can't get in because it too big'; 'It lets some things in and out but not everything'
3	*Multistructural*	'By how big or how it is shaped or can it travel through the tails of the cell'; 'Well, there has to be an equal amount of one thing on the inside and outside. Only some things make it in. The things have one way to go in and out'
4	*Relational*	'This means that the cell membrane only lets certain things in. Small things such as oxygen and water can get through the heads and tails. Negative charged things can too. Large things like glucose must enter through a protein channel. Also positive charged substance must enter or exit through a protein channel'
5	*Extended Abstract*	'A selectively permeable barrier is a barrier that lets certain things in and keeps certain things out, like a bouncer. It identifies resources and lets them in, like a castle with a gate. In the case of a cell, substances are selected according to its shape, size, and chemical charge'

groups was undertaken. To investigate whether statistically significant differences existed between the two treatment groups a simple gain score approach was employed. Given the ordinal nature of the data, difference scores were compared using the Mann–Whitney *U*-test ($\alpha = .05$).

Results and Discussion

Distribution of Responses

Table 3 presents the distribution of pre-test and post-test SOLO levels according to the treatment group. Visual inspection of these data indicates that both treatment groups entered the study with similar levels of understanding regarding the cell membrane's selective permeability. Conversely, post-intervention SOLO levels

Table 3. Pre-test and post-test SOLO level distribution

		Pre-test comparison		Post-test comparison	
SOLO level	Code	Visual group	V + H group	Visual group	V + H group
Prestructural	1	30 (75)	31 (77.5)	14 (35)	11 (27.5)
Unistructural	2	10 (25)	8 (20)	22 (55)	16 (40)
Multistructural	3	0 (0)	1 (2.5)	3 (7.5)	5 (12.5)
Relational	4	0 (0)	0 (0)	1 (0)	7 (17.5)
Extended Abstract	5	0 (0)	0 (0)	0 (0)	1 (2.5)

Note: Data presented as frequency (%).

Table 4. Difference scores across treatment groups

Difference score	Visual group (n = 40)	V + H group (n = 40)
–1	2 (5)	0 (0)
0	17 (42.5)	14 (35)
1	18 (45)	15 (37.5)
2	3 (7.5)	7 (17.5)
3	0 (0)	4 (10)
4	0 (0)	0 (0)

Note: Data presented as frequency (%).

diverged a bit. That is, there were more students from the V + H group whose responses reached the higher (4 and 5) SOLO levels.

Changes in SOLO Level

Table 4 presents the frequency distribution of the difference scores and Figure 4 represents these data graphically. The results of these analyses suggest that the difference scores varied across the two treatment groups. Here, no students in the V + H group showed negative gains, and many more students in this group moved up two or three levels according to the SOLO taxonomy.

The results of the Mann–Whitney *U*-test (α = .05), presented in Table 5, indicate that the difference scores (Visual group: mean rank = 35.59, sum of ranks = 1,423.50; V + H group: mean rank = 45.41, sum of ranks = 1,816.50) were significantly different between the treatment groups, U = 603.50, p = .043.

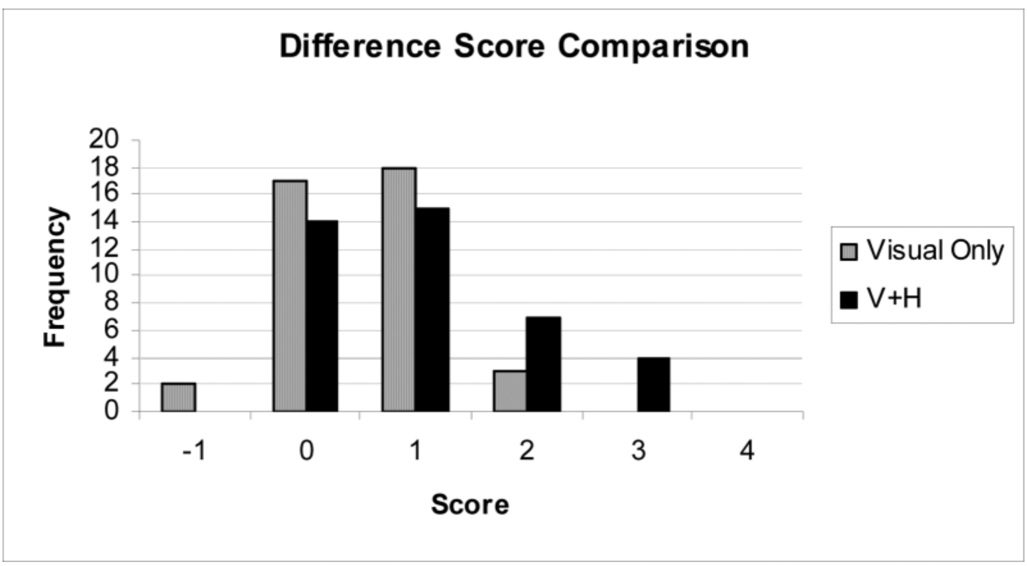

Figure 4. Comparison of difference scores across treatment groups

Table 5. Comparison of mean difference scores across treatment groups

Assessment	Visual group (n = 40)		V + H group (n = 40)			
	Mean rank	Sum of ranks	Mean rank	Sum of ranks	U value	p value
The cell membrane is often described as a selectively permeable barrier. In your own words, explain what this means …	35.59	1,423.50	45.41	1,816.50	603.50	.043*

Note: The Mann–Whitney U-test was used to compare treatment groups. *$p < .05$.

These quantitative results are bolstered by a qualitative comparison of (some of) the groups' post-intervention responses. First we share some of the responses from students in the Visual group:

> I think it works as a wall or shield that keeps away the bad stuff and lets in the good and keeps the good in. (Level 2, *Unistructural*)

> This means that the cell will only let some things in for example it may let all small molecules in but not let all big molecules in. (Level 2, *Unistructural*)

> Well, there has to be an equal amount of one thing on the inside and outside. Only some things make it in. The things have one way to go in and out. (Level 3, *Multistructural*)

As a means of comparison we also depict several post-intervention responses from the V + H group:

> Maybe the substances like the 'heads and tails' let water and oxygen molecules through but they didn't let glucose through. I think that 'protein' or something was used because the glucose molecule felt too big to go through the 'heads and tails' so they got help from proteins. (Level 4, *Relational*)

> This means that the cell membrane only lets certain things in. Small things such as oxygen and water can slide through the heads and tails. Negative charged things can too. Large things like glucose are blocked and must enter through a protein channel. Also positive charged substance must enter or exit through a protein channel. (Level 4, *Relational*)

> Bigger molecules are most likely to use facilitated diffusion … oxygen is smaller so it passes through with ease. When there is the same amount of the same kind on the outside as the inside, it is called an equilibrium. Simple diffusion uses no energy while facilitated use energy. Facilitated (diffusion) helps molecules inside the cell. It opens up and the molecule gets pulled through a 'channel' the shape of the molecule. Then outer part closes and the inner opens to the inside of the cell. (Level 4, *Relational*)

Utility of the SOLO Taxonomy

We readily acknowledge that development of student understandings in science is a terribly complex process. Moreover, as we have stressed throughout this article, accurately measuring and classifying this process is extremely difficult. To this point it should be noted that there have been several previous intervention studies, set within the context of classroom science learning, which have investigated the impact of haptic feedback (e.g., Jones et al., 2003; Reiner, 1999; Williams et al., 2003). Although these studies commonly point to the positive affective influences of haptic feedback (e.g., increased interest and improved attitudes), attempts to isolate and document a cognitive impact has been met with much less success.

Being a response measure (not a measure of students' personological characteristics), the SOLO taxonomy is intended to be sensitive to instruction—and as such its stability from occasion to occasion is less important than intercoder agreement on a particular task (Biggs & Collis, 1982). Our application of the SOLO taxonomy as a diagnostic tool resulted in quantitative student outcome data that provide preliminary evidence that the addition of haptic feedback may have influenced the manner in which students came to understand the mechanism behind the cell membrane's selective permeability. The critical questions that remain unanswered regard the specific nature and persistence of this 'haptic influence'.

Impact of Haptic Feedback

Regardless of the treatment group, the majority of the students improved their understandings of this concept. This may not be surprising given that prior to the instructional intervention an overwhelming number of participants' responses (75% of the Visual group and 77.5% of the V + H group) were at the *Prestructural* level, suggesting virtually no knowledge about the topic. After experiencing the instructional programme, the numbers of responses falling into this category dropped to 35% and 27.5%, respectively.

But when one looks more closely at the distribution of these perceived cognitive improvements, it suggests that students receiving the haptic feedback were more likely to reach higher levels of sophistication in their understandings. That is, according to this assessment tool, more of these students were able to integrate concepts and ideas presented during the programme into a coherent whole, with the various parts contributing to an overall meaning of membrane permeability. This finding is also evidenced in the difference scores in which 17.5% of the V + H group moved up two SOLO levels compared with 7.5% of the Visual students. Additionally, 10% of the V + H students improved by three SOLO levels; no such gains were observed in students that relied only on visual information.

Such group difference may begin to lend credence to the philosophical and theoretical claims that have been made about the critical role of touch in the meaning-making process. The students in the V + H group were able interact with the computer-generated visualisations in ways that that vision alone simply did not allow. These students, receiving the haptic feedback, were able to 'grab hold of' the virtual substances and 'feel' how each reacted when it came into contact with the membrane structure. More precisely, they could sense that the small oxygen molecules could pass through the phospholipid bi-layer without resistance. Additionally, they could 'feel' that the relatively large glucose molecule was 'blocked' and thus not able to pass through the membrane in this manner. They went on to discover that the glucose molecule must fit into the protein channel, which triggers a conformational change that transports the molecule to the inside of the cell. Students in this group were also able to 'experience' that, despite its small size, the potassium ion is not able to pass through the heads and tails of the bi-layer. Instead they figured out that the ion, due to its chemical charge, must use a different protein channel to enter the cell. In this case these students could 'feel' the ion being pulled rapidly through the water-filled protein channel.

From a constructivist's perspective, learning is described as the active construction of knowledge as sensory data are given meaning of prior knowledge (Tobin, 1990). Perhaps it is the addition of the simulated sense of touch, both tactile and kinesthetic in nature, afforded by the haptic device that improved students' ability to integrate the critical components of the concept and build more connected understandings of the complex biological process that was being modelled. It may be that students receiving bi-modal feedback were better able to 'develop understanding as appreciating relationships' as described by the *Relational* level of the SOLO taxonomy.

Limitations and Future Work

As alluded to previously, we found some early evidence suggesting that the haptic augmentation of computer-based science simulations leads to a deeper level of processing. Certainly more research is needed to determine whether the observed effects persist with a larger number of students and across a variety of open-ended questions and assessment tasks. Although interesting and encouraging, the results of this work should be interpreted with the study's limitations in mind.

Scoring Issues

While we found the SOLO taxonomy to be a useful tool that aided us as we attempted to assess the cognitive impact of haptic feedback, its application does not guarantee an accurate and complete account of what was learned. We readily acknowledge that there is always some degree of subjectivity at play when scoring rubrics are used. For example, some readers may question our example of a Level 5 (*Extended Abstract*) response in Table 2. Here the student explains that:

> A selectively permeable barrier is a barrier that lets certain things in and keeps certain things out, like a bouncer. It identifies resources and lets them in, like a castle with a gate. In the case of a cell, substances are selected according to its shape, size, and chemical charge.

Particularly, insightful readers may suggest that this, somewhat anthropomorphic, response does not exhibit the same level of detail about specific membrane mechanisms as the illustrative Level 4 explanation in Table 2. However, in our initial scoring we felt that this response indicated that the student 'reconceptualized the concepts at a higher level of abstraction' (i.e., a spontaneously generated analogy) as described by the SOLO taxonomy, and thus we scored it as a 5. It should be noted here that in this particular study this was the only response given a Level 5 (*Extended Abstract*) score and, to test the impact of this single questionable score on the overall results, we rescored this response (giving it a 4 rather than a 5) and re-ran the analysis. As one might expect, this had a negligible impact (Visual group: mean rank =35.63, sum of ranks = 1,425.00; V + H group: mean rank = 45.38, sum of ranks = 1,815.00; $p = .044$). But certainly this above example highlights the need to apply diagnostic assessment schemes, such as the SOLO taxonomy, with its inherent limitations in mind.

A related issue is the somewhat moderate level of intercoder reliability (0.83) that was found in this study. One cause of this may be attributed to the brevity of student responses. That is, perhaps lengthier work samples would have made discerning the students' level of understanding more precise. It has also been suggested (Chan, Tsu, Chan, & Hong, 2002) that the creation and use of sublevels can reduce the ambiguity of the SOLO model. These researchers utilised a nine-level taxonomy that makes a distinction between low-level, moderate-level, and high-level *Multistructural* and *Relational* (Level 3 and Level 4) responses. They report that using this modified version resulted in higher inter-rater reliability coefficients when compared with the original five-level SOLO taxonomy (Chan et al., 2002).

Restricted Written Responses

The current difficulties regarding the accurate and complete assessment of students' understandings in sensorily rich learning environments is in part due to the complicated interface among words, internal representations, and physical environments. We view the scoring of student responses using the SOLO taxonomy (as depicted in this study) to be a critical but somewhat restricted first step in the development of an assessment scheme that is truly sensitive to the effects (or lack there of) of haptic feedback.

Perhaps surprisingly, very few of the experimental group's responses showed haptic links. That is, only a few students (the ones cited in the previous section) provided written answers that show direct evidence of haptic interaction. One plausible explanation of this intriguing finding is that the haptic aspects modelled may very well be facilitating student cognition at a *non-verbal level*.

It may be that examining student responses through a Perceptual Symbol System (Barsalou, 1999) lens can help researchers in this field make more specific judgements about qualitative aspects of situational information that has been captured and activated in mental representations and that subsequently make their way into students' responses on assessment items.

While a complete and just discussion of this complex theory lies well beyond the aim and scope of this particular article, in brief it suggests that modality-specific simulations underlie the representation of concepts. Barsalou's 'symbols' do not carry the traditional meaning in that they by themselves do not stand for something in the world. Rather, according to Barsalou (1999, 2003), perceptual symbols combine to form constituent units of knowledge, called *simulators*. These simulators develop from modality-specific representations that are activated during exposure to objects and events (Barsalou, Simmons, Barbey, & Wilson, 2003). Simulators bind situational attributes (e.g., orientation, size, shape, colour, hardness, roughness, compliance, resistance) to perceptual symbols. The perceptual symbols are then meshed to generate an unlimited number of dynamic simulations. Moreover, these perceptual symbols operate to simulate the experience of what some linguistic description refers to.

A Novel Approach

While the study being reported here did not yield the data necessary to employ such an investigatory model directly, future efforts will be directed towards the refinement of current assessment taxonomies to include gradations of conceptualisation directly related to haptic interactions. One way to do this is to identify and describe a portable set of core *haptic simulators*, as well as study-specific context-dependent *haptic simulators*.

Examples of the former would include: object properties such as texture (roughness/smoothness, hardness/softness, wetness/dryness, stickiness, and slipperiness), compliance, temperature, weight, shape, and part motion (Lederman & Klatzky, 1987). With the current study in mind, illustrations of the latter (context-dependent *haptic simulators*) could be the surface compliance of the cellular membrane, the sinuous shape of the hydrophobic tails, viscosity differences within the phospholipid bi-layer, the specific shape of carrier protein receptor sites, and the pull of ions through the protein channel.

Armed with this theoretical model, researchers could take a more systematic approach to the analyses of the influence of haptic feedback on student cognition. By focusing on *observables* or the manifest behaviours of individuals and groups, researchers would be better able to make informed inferences regarding the efficacy of this emerging technology (Eisner, 1981).

More precisely, investigators could examine *words* (i.e., what users say) and *actions* (i.e., what users do), count these incidences, and once counted treat these incidences in various ways to build more robust explanations and extend theories regarding the cognitive influence of simulated touch. That is, these recorded *observables* (e.g., words and actions) could be attributed to the existence of *perceptual symbols* and the construction of *haptic simulators* in the meaning-making process. Again using the current study to elucidate this idea, Figure 5 depicts a hypothetical example of how such a perceptual symbol systems approach might play out in future haptics research.

Finally, underscoring the prospective nature of this study, we acknowledge that the feasibility of conducting a large-scale study of the implications of haptic feedback on student learning is still questionable. While the price of haptic interfaces have dropped considerably since their debut decade ago, it is still unlikely that one would find an existing school computer laboratory outfitted with them. But perhaps the combined affects of refined analytical approaches, sound theory building, a growing empirical research base, and more affordable interfaces will lead to an increased and (perhaps more importantly) prudent use of haptics in the teaching and learning of school science.

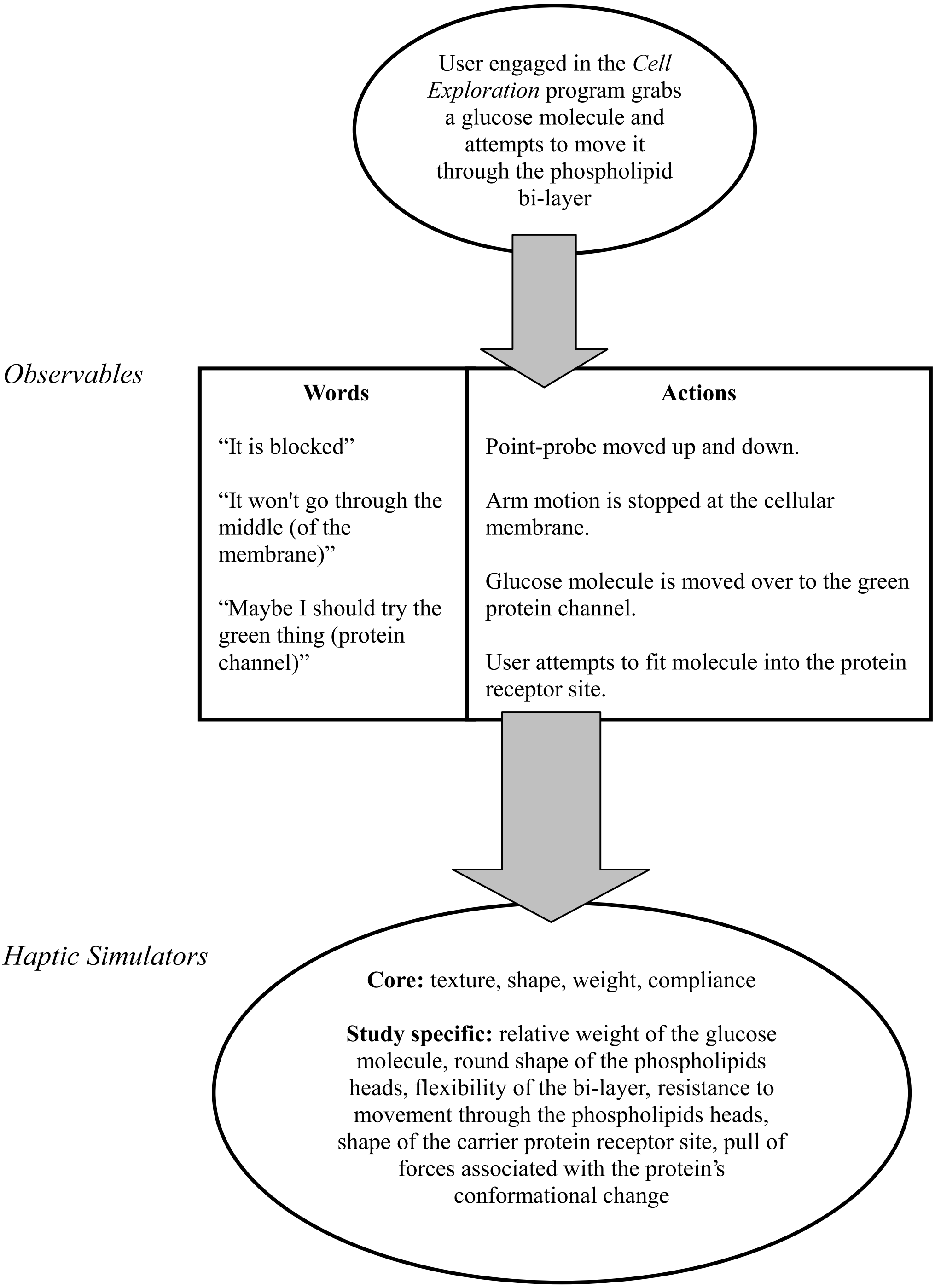

Figure 5. Hypothetical illustration of a haptic perceptual symbol systems analytical approach

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Appendix A. Cell Exploration Guide

This document serves as a template for the researcher as he/she guides the student through the instructional program. Its intent is to highlight the essential information that all students should attend to and is formatted as a script.

[suggested answers with key concept(s) underlined]

Part I: The Cell Membrane

A) Exploration:

Researcher: *In this section you will have the opportunity to get a close-up view of the cell membrane's structure and explore its parts. You will have* ***10 minutes*** *for this section.*

B) Review:

Researcher: *Describe the phospholipids that make up the cell membrane.* (Prompt if needed: What are the two parts that make up the phospholipids?)

[the molecules that make up the bi-layer of the cell membrane; have a hydrophilic 'head' and a hydrophobic 'tail' region.]

Researcher: *How do the heads and tails of these phospholipids differ?*

['Heads' are hydrophilic which means 'water-loving'; these substances are attracted to water. 'Tails' are hydrophobic which means 'water fearing'; these substances are not attracted to water.]

Part II: Passive Transport

A) Exploration:

Researcher: *Next, you are able to investigate how certain materials can pass into and out of the cell. Follow the on-screen directions, your goal is to grab the molecules and pass them through the cell membrane until equilibrium is reached. You will have* ***20 minutes*** *for this section.*

Researcher: *Name some of substances that may need to pass through the cell membrane.*

[glucose (sugar), oxygen, water, & potassium ions]

Researcher: *Why did some molecules pass through the center of the cell membrane (the phospholipids) and others did not?*

[glucose is too large to pass through the bi-lipid portion membrane so it uses protein channels to help (facilitate) its transport; oxygen is gaseous, small, & non-polar so it can easily pass through the bi-lipid layer; water is polar but small enough (we think) to pass through the bi-lipid layer; potassium ions are small but charged and can not pass through the bi-lipid layer & need to pass through a protein channel which creates a water-filled cavity that allows the charged particle to pass through.]