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The impact of students' exploration strategies in discovery-based instructional software

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Abstract: Active learning is a key element of constructivist learning theory and has been used as an argument for employing discovery-based designs with instructional software. On the other hand, researchers have highlighted empirical evidence showing that 'pure' discovery-based learning is of limited value. This suggests that *how* learners interact is important in predicting whether learning occurs. This paper reports on a study of 158 university students who each used two instructional simulations – one with a discovery-based design and the other with a tutorial-based design. Students' learning outcomes were assessed via pre-tests and post-tests of conceptual understanding. Students' interactions using the discovery-based program were recorded and coded as either systematic or unsystematic. The results showed that when compared with the tutorial-based learning program systematic exploration resulted in learning benefits, while unsystematic exploration did not. These results have implications for the design of instructional software if such resources are to be used effectively.

Introduction

A key element of constructivist theories of learning is the idea that each person forms their own representation of knowledge, building on their individual experiences – an idea attributed primarily to Piaget (1973). This knowledge representation is constantly reviewed and revised as inconsistencies between the current knowledge representation and experience are encountered through active exploration (Bruner, 1962; Piaget, 1973). Piaget (1973) explains the learning process in terms of equilibration. Equilibration begins with the construction by the individual of their own internal knowledge representation, or in Piaget's terms they accommodate their knowledge representation to fit with their experience. Subsequent experiences that are consistent with this knowledge representation are then assimilated into their knowledge representation. New experiences that do not fit with their current knowledge representation result in a further accommodation of their knowledge representation to fit with this new experience.

This idea that learning involves active knowledge construction has been used in support of various learning design frameworks, including inquiry-based learning (particularly in the sciences), and discovery-based learning using educational multimedia and computer-based simulations. On the other hand, researchers such as Mayer (2004) and Kirschner, Sweller and Clarke (2006) have highlighted empirical evidence showing that 'pure' discovery-based learning is of limited value. This suggests that *how* learners interact is an important avenue for further research. Specifically, the relationship between a learner's interaction with an instructional software program and his or her cognition has been identified as an important factor in predicting whether learning occurs (see Kennedy, 2004). This paper reports on research investigating how learners' different exploration strategies impacted on their cognitive processes and consequently on their learning outcomes.

Background

Interest in the potential learning benefits of interactive multimedia over the past 15 to 20 years was driven initially by the advent of the personal computer and its evolving multimedia capabilities, and subsequently by the advent of the Internet, making resources more readily located and acquired. Early multimedia took the form of programmed instruction or tutorials in which the learner would work through a linear sequence of instructional screens or drill-and-practice activities which provided an opportunity for learners to perfect their responses with immediate feedback. These designs were typically based on behaviourist theories of learning and so limited choice was available to learners. More recently the range of instructional software available has expanded but this type is still widely available (eg. Mathletics).

Alternative types of multimedia software began to emerge in the 1990s, with resources like *Investigating Lake Iluka* (Harper, Hedberg & Brown, 1995) and the *Jasper Woodbury* series (Cognition and Technology Group At Vanderbilt, 1992), which allowed non-sequential inquiry-based exploration of a computer-based learning environment scaffolded by the provision of holistic problem scenarios. The design of these types of interactive learning environment has been underpinned by the principles of active, inquiry-based learning that occurs in context and promotes knowledge construction and articulation (see Duffy & Cunningham, 1996).

Early research questions included: how multiple media should be combined to present content; how multimedia information might be structured; how learners might control the pace or the route by which they

moved through the data; and how the interface might be designed so learners would know where to click. This research agenda led to numerous experimental studies drawing on cognitive theories through which principles for designers and developers were derived (eg. Chandler and Sweller, 1991; Mayer; 2001; Sweller, 2005). Another body of research in the field emerged in the form of small-scale naturalistic studies of the use of multimedia resources by learners in particular contexts resulting in the derivation of design guidelines incorporating active exploratory learning underpinned by constructivist approaches to teaching (eg. Harper & Hedberg, 1997; Herrington & Oliver, 2000). These two research agendas have developed in parallel and at times at odds with one another. Recently, Mayer's (2004) conclusion that unscaffolded discovery learning is of limited or no value has re-ignited debate over how much *direction* is optimal in the design and use of instructional software (see also Kirschner, Sweller & Clarke, 2006; Kapur, 2008; Hmelo-Silver, Duncan & Chinn, 2007)

In summary, despite changes in technology over the past decade, interactive multimedia remains relevant, while researchers' understanding of the role interactivity plays in learning is limited. It is well accepted from a theoretical standpoint that there is great potential in exploratory resources that allow learners to actively construct their own knowledge representation through interaction with the environment, however the empirical results are mixed. Consequently there is a need for further research that explores the relationship between the design of the resource, the interactive tasks undertaken by the learner, and the cognition and learning that occurs as a result.

The study described in this paper was intended to contribute to knowledge about the relationship between interactive learning and cognition through an exploration of the learning performance of students using a multimedia resource with a discovery-based design compared to students using a resource with a tutorial-based design. As well as allowing for a direct comparison of the two groups the study also collected data on student prior knowledge, engagement and cognitive load as well as logging student interactions in order to characterise their exploration strategies. The focus of this paper is on the way in which exploration strategy affects learning performance. Future articles will report on the relationship between prior knowledge, engagement, cognitive load and learning performance.

Methodology

The study compared learning performance using a discovery-based design with performance using a tutorial-based design in each of two content domains, as shown in Table 1. The study was conducted with 158 University of Wollongong teacher education students. Each student completed a discovery-based learning condition using a multimedia resource focussing on one content domain and a tutorial-based learning condition using a multimedia resource focussing on the other content domain. The order was varied so that approximately half of the students undertook their tutorial learning condition first while the other half undertook their discovery learning condition first. Prior to each learning condition the students completed a knowledge pre-test. After each learning condition the students completed a knowledge post-test and a questionnaire with engagement and cognitive load items. Student actions within the learning resources were also logged to allow later analysis of their exploration strategies. For analysis purposes the two content domains were treated as distinct experiments. In each case the independent variable was learning condition, with two levels, Tutorial and Discovery, and the dependent variable was learning performance. The decision to essentially undertake two concurrent experiments using two distinct content domains and two distinct sets of multimedia resources was made because, being mindful of the potential for content or resource specific factors to impact on the results, we were keen to have two distinct data sets to draw upon in making conclusions from the data. The content domains, blood alcohol concentration and global warming, were chosen because of their widespread interest within the likely participant community.

Table 1: Experimental Design

	Content Domain	
Condition	Blood Alcohol Concentration	Global Warming
Tutorial	N=73	N=85
Discovery	N=85	N=73

To address issues encountered in earlier studies (see, for example, Dalgarno, Bennett & Harper, 2010), resources and learning tasks were designed to ensure alignment with the intended learning outcomes. The discovery resources were designed around a 'predict-observe-explain' learning design (White & Gunstone, 1992), with students encouraged to mentally predict the effect of their simulation parameter changes, observe the results of the change and mentally try to explain the observed results. Figures 1 and 2 provide excerpts from the discovery-based resources showing the screens on which participants could change variables on the left-hand side of the screen before running the simulation to see the results. In the case of global warming, the four graphs on the right-hand side of the screen, showing values for ozone layer thickness, CO_2 concentration,

greenhouse insulation and surface temperature, changed if the variables were altered. In the blood alcohol concentration simulation the graph on the right-hand side showing values for blood alcohol concentration over time, changed if the input variables were altered. As far as possible the user interface was consistent across the two topics to maximise comparability between the resources.
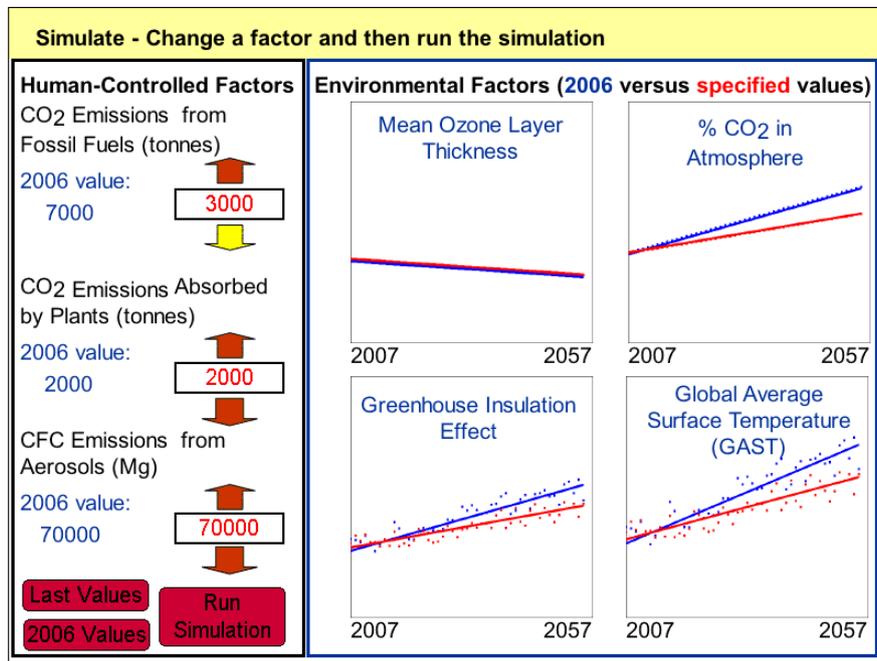

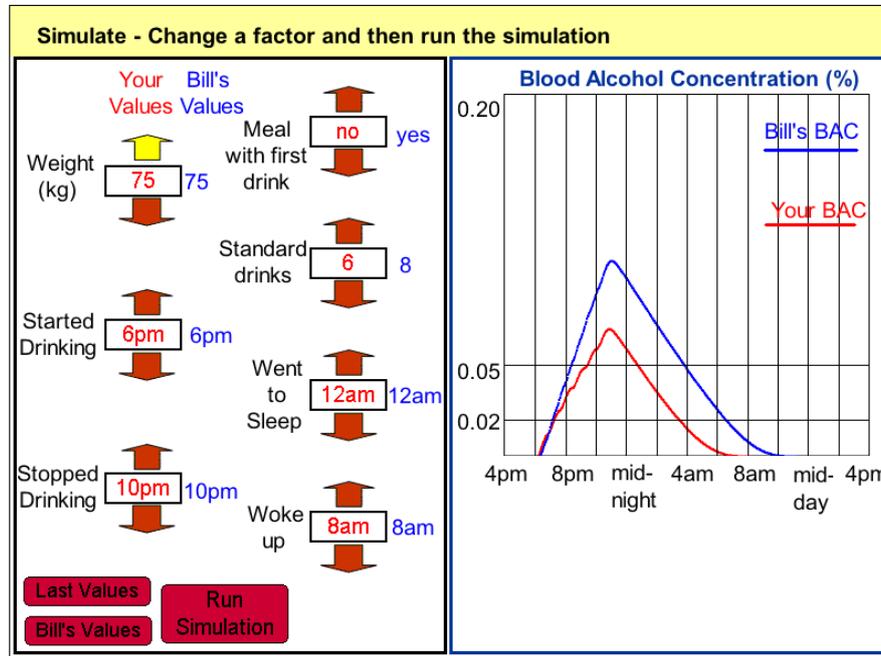Figure 1. Excerpt from the Global Warming Discovery Resource

Figure 2. Excerpt from the Blood Alcohol Concentration Discovery Resource

The tutorial-based resources for each topic area were created from the discovery resource, but instead of allowing students to change the variables a series of pre-defined values and the relevant graphical outputs were shown. Students were provided with a single option, a continue button, which resulted in the next set of pre-defined values being loaded and the corresponding output displayed. This is illustrated in Figures 3 and 4.
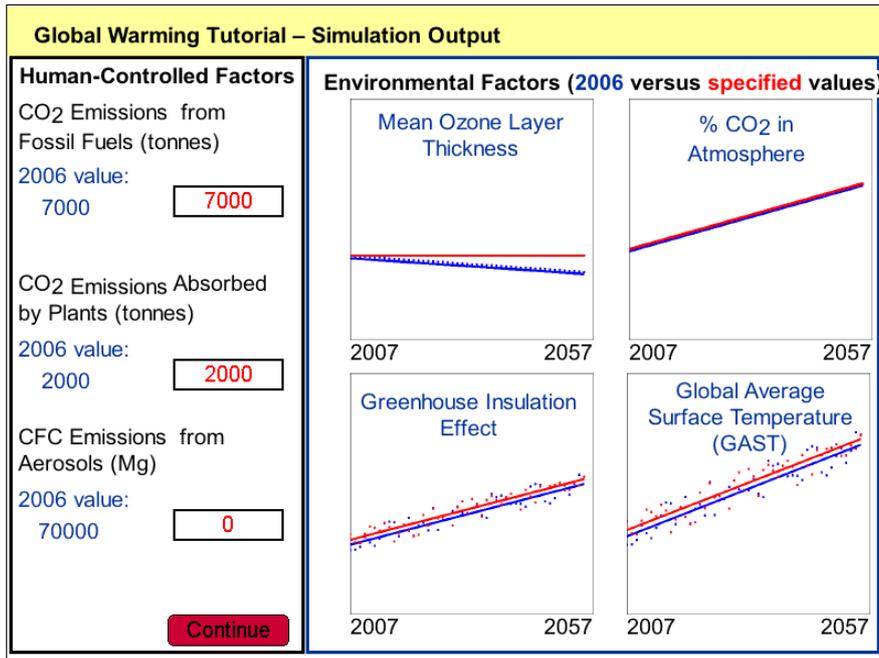
Global Warming Tutorial – Simulation Output

Human-Controlled Factors

CO_2 Emissions from Fossil Fuels (tonnes)

2006 value:
7000   7000

CO_2 Emissions Absorbed by Plants (tonnes)

2006 value:
2000   2000

CFC Emissions from Aerosols (Mg)

2006 value:
70000   0

Continue

Environmental Factors (2006 versus specified values)

Mean Ozone Layer Thickness
2007   2057

% CO_2 in Atmosphere
2007   2057

Greenhouse Insulation Effect
2007   2057

Global Average Surface Temperature (GAST)
2007   2057

Figure 3. Excerpt from the Global Warming Tutorial Resource

Blood Alcohol Tutorial – Simulation Output

Tom's Values   Bill's Values

Meal with first drink   yes   yes

Weight (kg)   110   75

Standard drinks   8   8

Started Drinking   6pm   6pm

Went to Sleep   12am   12am

Stopped Drinking   10pm   10pm

Woke up   8am   8am

Continue

Blood Alcohol Concentration (%)

0.20

Bill's BAC

Tom's BAC

0.05

0.02

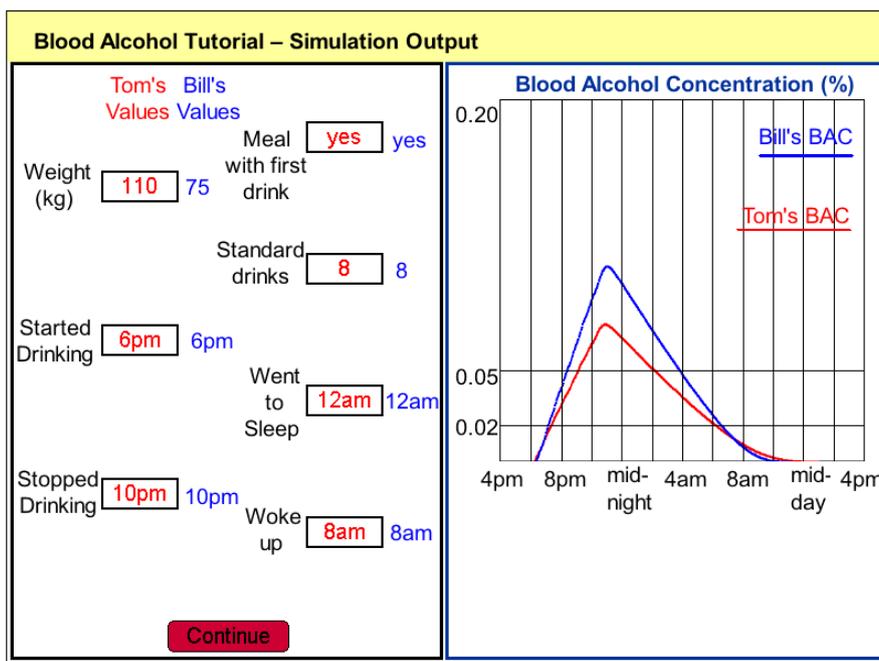4pm   8pm   mid-night   4am   8am   mid-day   4pm

Figure 4. Excerpt from the Blood Alcohol Concentration Tutorial Resource

The knowledge pre-tests and post-tests contained a series of identical items designed to measure understanding of key concepts within the content area. For example, within the Blood Alcohol Concentration content area, the following item was included within the pre-test and post-test to explore the participants' understanding of the relationship between of a person's weight and their blood alcohol concentration:

A person with greater body weight:
a) Will have a higher Blood Alcohol Concentration (BAC) than a lighter person.
b) Will have a lower BAC than a lighter person.
c) Will have the same BAC as a lighter person.
d) Will have their BAC increase at a greater rate than a lighter person

The following item was included within the Global Warming pre-test and post-test to test the participants on their understanding of the way various environmental factors affect the global temperature:

> *Which of the following environmental factors have a direct or an indirect effect on the Global Average Surface Temperature (GAST)?*
> a) *The amount of Carbon Dioxide (CO2) absorbed by plants*
> b) *The thickness of the ozone layer*
> c) *The percentage of CO2 in the atmosphere*
> d) *The Greenhouse insulation effect*

Some questions were specifically designed to test whether participants held certain common misconceptions within each content area. Some of the questions, such as the Global Warming example question above, had multiple correct stems while some, such as the Blood Alcohol Concentration example question above, had a single correct stem. Students scored one point for each question in which only the correct stems were chosen. There were seven questions in the Global Warming test and nine questions in the Blood Alcohol Concentration test.

Results

The first analysis considered whether participants who had completed the program with a discovery-based or tutorial-based learning design showed improved understanding. As shown in Table 2, an initial analysis of the learning which occurred in each condition was undertaken using paired T tests which compared the Pre-Test and Post-Test scores. The results of this analysis indicated that for the Global Warming content area, which participants found quite challenging, there was a slight decrease in test performance from the Pre-Test to the Post-Test by Tutorial participants and no difference in performance for Discovery participants. For the Blood Alcohol Concentration content area there was no difference in test performance for the Tutorial participants and an increase for Discovery participants.

For each content domain (Global Warming and Blood Alcohol Concentration) an analysis of covariance (ANCOVA) test was completed which included post-test score as the dependent variable, learning design condition as the independent variable (discovery, tutorial), and pre-test score as a covariate. For the Global Warming content domain there was no effect for condition ($F_{(1,155)} = 2.40$; $p = .124$) but there was a significant effect for participants' pre-test scores on their post-test understanding ($F_{(1,155)} = 27.50$; $p < .001$). For the Blood Alcohol Concentration, there was an effect for both condition ($F_{(1, 155)} = 5.52$; $p = .02$) and the participants pre-test scores on their post test understanding ($F_{(1,155)} = 16.40$; $p < .001$). It can be seen from the mean scores and standard deviations presented in Table 2, that despite these significant result, particularly in the content area of Blood Alcohol Concentration, in general participants showed very little improvement in performance from pre- to post-test, regardless of content domain or condition. Given the maximum scores that *could* be obtained by students, performance scores were well below the mid point of the scale for both content domains.

Table 2: Mean pre- and post-test scores for both conditions across the two content domains

Content Domain	Condition	Pre-Test M (SD)	Post Test M (SD)	T
Global Warming+	Tutorial (n=85)	1.82 (1.51)	1.42 (1.29)	2.26 (p=0.027)
	Discovery (n=73)	1.68 (1.42)	1.72 (1.85)	0.20 (p=0.841)
Blood Alcohol^	Tutorial (n=73)	3.55 (1.25)	3.42 (1.31)	0.60 (p=0.552)
	Discovery (n=85)	3.60 (1.24)	3.93 (1.40)	2.33 (p=0.022)

+max = 7; ^max = 9

We also noticed that the variance in post-test scores for participants' discovery-based condition, particularly for the global warming content domain, was quite high; and we wondered whether there may be variation within the discovery-based group that reflected differences in how the simulation was used and explored by participants. A preliminary analysis showed that some participants seemed to have explored the simulation systematically and others were more unsystematic in their approach. Given this, we characterised participants' strategies while interacting with the simulation-based learning activity as *Systematic Discovery* if they investigated the content area by 'running' the simulation by changing only one variable from the provided example (e.g. 'Bill's values' or '2006 values') or from previous simulation outputs on four or more occasions. All other discovery participants' strategies were classified as *Non Systematic Discovery.*

Table 3 shows the implicit experimental design once the discovery participants were separated into two groups using this characterisation. The new design again has learning condition as the independent variable, but with three levels, Tutorial, Non-Systematic Discovery and Systematic Discovery. The criteria and thresholds for distinguishing between non-systematic and systematic discovery participants could have been arrived at in a number of ways. We experimented with cluster analysis using a number of the indicators of exploration approach (time spent, iterations undertaken, variables changed etc) but ultimately decided to use the number of variables changed as a simple, intuitively meaningful criteria, and chose thresholds that ensured sufficiently sized and meaningful sub-groups.

In order to investigate whether this characterisation of participants' exploration strategies in the simulator was better able to account for variance in post-test performance scores, an ANCOVA for each content area was again calculated but this time with a three-level independent variable (tutorial, non-systematic discovery, and systematic discovery), as shown in Table 4. For both content domains there were again significant covariate effects for the pre-test scores on the post-test scores (Global Warming ($F_{(1,154)} = 23.72$; $p < .001$); Blood Alcohol ($F_{(1,154)} = 23.72$; $p < .001$)). Main effects for condition were also recorded for both content domains. In both content domains the pattern of results was the same. After accounting for pre-test knowledge, post-test comparisons indicated that participants who were in the systematic discovery group recorded significantly higher post-test scores than participants in both the non-systematic discovery and the tutorial groups. Interestingly, there were no differences between these latter two groups in terms of their understanding (post-test) for either content domain.

Table 3: Experimental Design after Characterising Discovery Strategies

	Content Domain	
Condition	Blood Alcohol Concentration	Global Warming
Tutorial	N=73	N=85
Non-Systematic Discovery	N=51	N=48
Systematic Discovery	N=34	N=25

Table 4: Significant main effects for condition (three levels) across the two content domains

Content Domain	Post-Test Tutorial M (SD)	Post-Test Non Systematic Discovery M (SD)	Post-Test Systematic Discovery M (SD)	F	p
Global Warming+	1.42 (1.29) [a]	1.33 (1.52) [a]	2.48 (2.20) [b]	4.17	.017
Blood Alcohol^	3.42 (1.31) [a]	3.51 (1.30) [a]	4.56 (1.33) [b]	8.69	<.001

[ab] different superscript across rows indicate between group differences ($p < .001$).

Discussion

Take Home Messages and Implications

The comparison of the post-test performance of students who undertook their learning using a learning resource with a tutorial-based design with those who used a resource with a discovery-based design found a small but significant difference in test performance in one content domain and no significant difference in the other. This absence of a consistent benefit for pure discovery learning is consistent with Mayer's (2004) argument against the use of such learning designs. However, when the exploration strategies of participants using the discovery-based resources were analysed it became clear that some students explored in a systematic fashion and some did not, and that there was a clear difference in test performance of systematic and unsystematic explorers within

each content area. Additionally, systematic explorers in each content area performed significantly better than tutorial participants.

This suggests that, contrary to Mayer's (2004) arguments, for some students, an active discovery-based design may be ideal. However, for others, the benefits of active exploration are countered by the confusion caused by unsystematic exploration strategies and consequently they do no better than tutorial participants. An important question, then, is what led some students to explore the simulation systematically and others non-systematically. Kirschner, Sweller and Clarke (2006) suggest that the value of instructional guidance only begins to diminish when learners have sufficient prior knowledge to allow for *internal guidance*. On the other hand, it may be that some learners have a natural aptitude for systematic exploration or through prior experience of more structured inquiry-based learning designs, such as problem-based learning (see Hmelo-Silver, Duncan & Chinn, 2007), they have developed more systematic exploratory approaches.

The concept of *scaffolding* (Wood, Bruner, & Ross, 1976) is helpful in thinking about learning designs which capitalise on Piaget's ideas about active learning while providing sufficient guidance to help prevent the learner becoming confused. Scaffolding could be provided by a teacher, with the simulation explored by a student on an interactive whiteboard while the teacher directs students' attention to the emergent concepts. Alternatively, the tutorial resource could be enhanced by the inclusion of explanatory text or audio, similarly directing the students' attention to the key concepts (see also Lee & Dalgarno, 2011, for a more detailed discussion of scaffolding in discovery-based learning environments).

Follow up Research

We are currently analysing the results of the engagement and cognitive load questionnaires to determine whether there is a relationship between resource type and these factors, or between these factors and learning outcomes. The relationship between prior knowledge and engagement and between prior knowledge and exploration strategy is another avenue being explored, which will help to inform on Kirschner, Sweller and Clarke's (2006) proposition that learners with higher prior knowledge have less need for instructional guidance. We have also undertaken a pilot study using the same experimental design but with participants in an MRI scanner to determine whether brain activation differences are evident between the two conditions (see Dalgarno, Kennedy & Bennett, 2010) and we are also currently analysing these results.

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