An fMRI study exploring cognitive processing during computer-based discovery learning

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Abstract

Discovery-based learning designs incorporating active exploration are common within computer-based instructional simulations, supported by constructivist theories of learning focussing on active individual knowledge construction. On the other hand, researchers have highlighted empirical evidence showing that ‘pure’ discovery learning is of limited value and that combinations of explicit instruction and guided discovery learning are more effective. Little is known, however, about differences in the cognitive processing that occurs when a learner undertakes active discovery learning using a computer-based simulation compared to when they are guided through observation of simulation output. A better understanding of the cognitive processing occurring when learners interact with on-line materials in the context of specific learning designs is important both for networked learning researchers and for on-line teachers.

This paper reports on a study in which the brain activations from two learning conditions using computer-based simulations were compared using functional magnetic resonance imaging (fMRI). One condition allowed exploration through manipulation of simulation parameters, while the other allowed observation of simulation output from preset parameters. Drawing on constructivist theories of learning, it was hypothesised that the active exploration condition would lead to greater activation of brain areas associated with working memory organisation and long term memory formation. The study also set out to explore the broader feasibility of using fMRI to explore learners’ cognitive processing while undertaking holistic learning activities using on-line learning materials.

Results of the study were somewhat equivocal about differences in brain activation with no consistent differences in activation between the two conditions able to be measured. Consistent with our related research which suggests that discovery learning strategies vary substantially across individuals, results of this study suggest that the cognitive processing during the two conditions varied across participants. Integrated analysis of the exploration processes, learning outcomes and measured brain activations of individuals shows promise in better understanding the relationship between learning strategy, interaction and cognition when using instructional simulations. Approaches like this that draw on an analysis of data on learning process and outcome along with an analysis of physiological measures (in this case blood flow as an indicator of brain activation) are expected to be at the leading edge of learning analytics research in coming years. The study also highlighted challenges associated with the use of fMRI to explore learners' cognition while undertaking learning activities allowing significant learner control and involving extensive computer-based interaction.

Keywords

Discovery learning, computer-based simulation, fMRI, cognition, interactivity

Background

Discovery learning

The notion of discovery learning has its origins in the 1960s, with Jerome Bruner one of the first to articulate in detail the potential benefits of instructional approaches with discovery learning at their core (Bruner, 1961). There are a range of related learning design approaches which are similar to or draw on elements of discovery learning, including exploratory learning (Reilly, 1974; De Freitas & Oliver, 2006), inquiry learning (Kuhn, Black, Keselman & Kaplan, 2000; Rutherford, 1964), and Problem Based Learning (Barrows & Tamblyn, 1980). Discovery learning and related learning design approaches have theoretical support in cognitive interpretations of constructivism which can be traced to Piaget's focus on active knowledge construction through exploration and interaction with one's environment (Duffy & Cunningham, 1996; Klahr & Nigam, 2004). The idea that learning involves active knowledge construction has particularly been used in support of inquiry-based learning approaches in the sciences, including discovery learning involving the use of computer-based simulations (De Jong & Van Joolingen, 1998).

In contrast to the well accepted theoretical support for discovery learning, a number of highly cited articles have questioned the value of discovery learning and particularly 'pure' discovery learning where little or no guidance is provided during the learning task. Mayer (2004), for example, reviewed three decades of research on discovery learning and concluded that in each case guided discovery learning was more effective than pure discovery learning. Kirschner, Sweller and Clark (2006), reached similar conclusions based on an argument grounded in current knowledge about cognitive architecture, expert-novice differences and cognitive load. Most recently, Alferi, Brooks, Aldrich and Tenenbaum (2011) in a meta analysis of 164 empirical studies of learning using discovery-based approaches concluded that explicit instruction is more effective than unassisted discovery, while discovery enhanced by the inclusion of guidance during learning was more effective than both unassisted discovery and explicit forms of instruction.

Computer-based simulations

A popular manifestation of discovery learning approaches have been computer-based instructional simulations focussing on the learning of conceptual material in the sciences (De Jong & Van Joolingen, 1998). These simulations 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 underpinned by the provision of holistic problem scenarios. It is generally acknowledged that a key advantage such resources have over alternatives such as video, is the capacity for high levels of learner-computer interaction and engagement (Rieber, 2005). It has been suggested that interactive learning tasks carried out in the context of an authentic, problem-based scenario will result in deeper, elaborative cognitive processing leading to greater conceptual understanding of the material presented (Rieber, 2005). A crucial focus of ongoing research has been the nature of the learner-computer interaction and the connection between the different types of interaction and the desired learning processes and outcomes (Sims, 1997).

Cognitive processing

Given the contention in the literature about whether active discovery learning is an effective approach to learning, an important question is whether there are measurable differences in the cognitive processing that occurs when learners undertake active exploration of an environment compared to when they engage more passively with visual information provided to them in a predetermined way. Cognition and learning theory suggests that, compared to users of tutorial-based instructional software, users of discovery-based software should experience greater degrees of elaborative processing and consequently form a greater number of semantic memory links through regularly drawing on their current understanding in making decisions and predicting how the simulated environment will respond (see Craik & Lockhart, 1972; Wittrock, 1994; Norman & Schmidt, 1992). Thus active exploratory learners would be expected to show greater activation in areas of the brain associated with information manipulation and long-term memory storage and retrieval, compared with more passive learners. Such areas include the prefrontal cortex and the medial temporal lobe, especially the hippocampus (Fernandez & Tendolker, 2001; Blumenfeld & Ranganath, 2006; Prince, Daselaar & Cabeza, 2005).

Methods

Traditional methods

Research methods that have been used to investigate cognition and learning have traditionally included observation, self-report questionnaires, focus groups, interviews and think-aloud protocols (Miles & Huberman, 1994; Ericson & Simon, 1993). In educational technology and human-computer interaction research these methods have been supplemented by the use of interaction log file or 'audit trail' analysis (Kennedy & Judd, 2004). While all of these techniques help researchers understand students' learning processes, all are limited in that they rely either on self-report or behavioural information to speculate about the cognitive activity of users. Consequently, although there is still a great deal that can be accomplished in addressing our research problem using these traditional methods, there may also be value in looking beyond these methods.

The alternative: functional brain imaging

An alternative approach to exploring cognition is to use functional brain imaging methods, such as functional magnetic resonance imaging (fMRI) to make inferences about the brain activation occurring during certain tasks. In recent years, the increased availability of imaging equipment and the more widespread knowledge of associated research procedures, have led to the use of such methods in a wide range of fields. FMRI is the most commonly used technology for functional brain imaging. FMRI requires similar but more sophisticated equipment to clinical MRI. It involves the measurement of regional responses to fluctuations in magnetic fields, which correlate with blood flow and in turn brain activation. The participant's head and upper body lie inside the scanner and remain completely still throughout the procedure. An angled mirror allows the participant to view a projected computer image while using a hand-held button pad or a special purpose mouse to operate the computer.

The functional imaging research to date has led to a large body of results identifying the neural-correlates of specific cognitive tasks. This body of data can be drawn upon in interpreting the results of functional imaging studies involving more holistic tasks, such as exploratory learning tasks using instructional software. For example, if a region of the brain associated with the storage of semantic information in long term memory is found to be activated to a greater extent during an interactive task than during attendance to the same information in a non-interactive fashion, then this might suggest that the interactivity could be contributing to retention.

It is important to note, however, that the results to date have not established a one-to-one relationship between cognitive tasks and brain areas. Cognitive tasks typically result in activation of a range of brain areas, and certain brain areas are activated by a range of different cognitive tasks. This is particularly the case for tasks involving higher order thinking. Nevertheless, in undertaking this study we were confident that sufficient data was available to allow comparisons between the cognition implied by brain activation measured during the use of instructional software and the cognition proposed by theory, and consequently to determine whether the activation is consistent or inconsistent with theory.

Methods used in this study

This study used a combination of traditional data collection methods with functional brain imaging techniques. The participants' cognitive processing and learning outcomes in response to each of the two learning conditions (exploration and observation) were explored using a range of data collection methods, including written pre- and post-tests; questionnaires on engagement and motivation; log files showing behavioural interactivity; stimulated response interviews involving the playback of the participant's recorded interactive session; and functional magnetic resonance imaging (fMRI) to infer brain activation. After two pilot studies each involving a single participant, the main study was carried out using eight participants. This paper reports on the fMRI results.

Four computer-based simulation resources were designed for the purposes of the study: an exploration and an observation resource focussing on each of global warming and blood alcohol concentration. Each participant used the exploration resource from one problem domain and the observation resource from the other. The following were the key features of the resources used in the study:

- Each resource was divided into two parts, a 'Background' section and a 'Main' section.
- The Background section consisted of screens containing background information about the problem domain.
- The Main section of the exploration and observation resources had identical screen layouts and both contained a regular baseline stimulus condition (a 'Rest Screen'), consisting of random numbers and graphs and an animated highlight.
- The Main section of the observation resources consisted of a series of 'Output Screens' showing the results of the simulation but without the ability to control the simulation parameters, shown alternately with the 'Rest' screen.

- The Main section of the exploration resources were structured to isolate the different cognitive functions associated with the task; so, participants planned their manipulations on one screen (the ‘Planning Screen’), carried out their manipulations on another (the ‘Manipulation Screen’), and viewed the output on a third (the ‘Output Screen’), with the ‘Rest Screen’ shown in between the ‘Output’ and ‘Planning’ screens during each cycle.
- Interaction occurred through the use of a three button device, with the left and right buttons moving a highlight forwards and backwards between options on the screen, and the middle button activating the highlighted option.

Figure 1 shows the Planning and Manipulation screens for the blood alcohol concentration exploration resource and Figure 2 shows the Output screen and Rest screen for this resource.

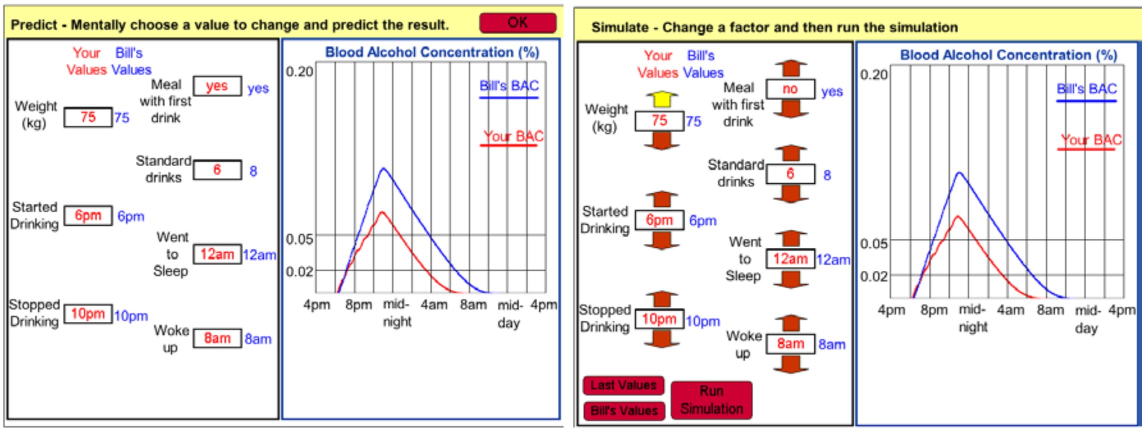

Figure 1. Planning screen (left) and Manipulation screen (right) from the blood alcohol concentration exploration resource.

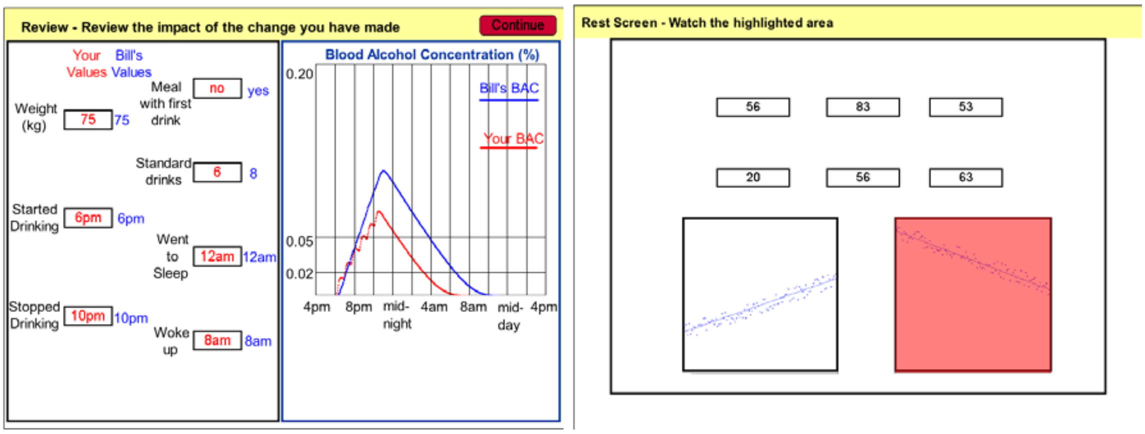

Figure 2.
Simulation output screen (left) and Rest screen (right) from the blood alcohol concentration exploration resource.

Functional magnetic resonance imaging was performed using a 3 Tesla Siemens Tim Trio scanner. Echo Planer Imaging (EPI) sequences sensitive to blood-oxygenation-level-dependent (BOLD) contrast were used to acquire 44 slices per pass with a repetition time (TR) of 3 seconds. T1 and T2 structural images were also acquired from each participant.

Results and analysis

The fMRI results were analysed using the software package Statistical Parametric Mapping (SPM) as follows:

- The following series of pre-processing steps were carried out on each participant’s data:

    - Slice-timing correction;
    - Motion correction;
    - Co-registration between the functional and structural images; and
    - Normalisation to map the functional and structural images to a common brain template (based on the atlas described by Talairach and Tournoux (1988));
- First-level analyses consisting of a series of within-subject voxel by voxel comparisons (T-tests) were carried out to compare the magnitude of the hemodynamic response during different parts of the learning task for each participant; and
- Second-level analyses were carried out consisting of the same voxel by voxel comparisons across the group of eight participants.
- To address the potential for false positives due to the large number of comparisons being performed, comparisons were corrected using the Family Wise Error (FWE) method with a p value of 0.05.

The first-level analysis used t-tests to compare, for each voxel within the brain, the blood flow as inferred by the hemodynamic response measured using fMRI occurring during specific periods in a participants learning. The relative level of activation of each of the parts of the brain containing these voxels can then be inferred (ie. activation has been found to correlate very highly with blood flow). For example, the blood flow (and thus activation) occurring when viewing the simulation output in the observation condition was compared to the activation during the rest periods, similarly the activation occurring when viewing the simulation output during the exploration condition was compared to rest activation, and the activation during simulation manipulation was also compared to rest activation. Finally the activation during viewing of simulation output during the exploration condition was compared to similar activation during the observation condition.

The output of the voxel by voxel t-tests carried out in SPM is a series of 'hot spots' expressed as x, y and z coordinates in Montreal Neurological Institute (MNI) space. Each of these hotspots is a point in 3D space where there are significant differences in activation for the two conditions being compared. These MNI coordinates were then converted to Talairach coordinates using the GingerALE software (see brainmap.org). These Talairach coordinates were then converted to named areas using the Talairach Client software which converts Talairach coordinates to brain area labels using Talairach Atlas terminology (see www.talairach.org). The Talairach Atlas labels brain areas at five levels: hemisphere, lobe, gyrus, tissue type, and cell type. The anatomic labels for these hot spots were also confirmed by redoing the analysis using un-normalised data and superimposing the identified hot spot locations on top of a structural image for each participant.

Table 1 summarises the comparisons performed and the major hot spots for each participant from the first-level analysis and across participants from the second-level analysis. The brain areas are reported in the table in order of significance according to the p values (ie. those with the lowest p values representing the highest probability of an actual difference between conditions are presented first in each cell). The brain areas where differential activation was found are reported in terms of the hemisphere and lobe in most cases, but for lobes with a wider range of functional characteristics, such as the frontal lobe and the limbic node, the gyrus is also reported.

For the second level analysis carried out across all participants, differential activation was found when comparing activation during the viewing of simulation output in the observation condition and activation during rest, and when comparing activation during simulation manipulation in the exploration condition and rest. Differential activation of the left frontal lobe pre-central gyrus and the right frontal lobe mid-frontal gyrus (contained within the left and right pre-frontal cortex respectively) when viewing simulation output in the observation condition is as expected. The pre-frontal cortex is associated with working memory organisation and plays a key role in long-term memory storage and retrieval. The differential activation in the parietal lobe for the exploration manipulation condition compared to rest is also understandable. The parietal lobe is associated with the integration of sensory information which is important in computer interaction through a visual interface.

The lack of significant differences in activation between viewing of simulation output and rest for exploration participants is unexpected. The fact that differential activation for this comparison was found for all except one participant suggests that rather than there being no difference between activation during rest and activation when viewing simulation output, the differential activation in this comparison across the group of participants varied in terms of the brain areas or voxels involved. The lack of any significant differences in activation when viewing simulation output between the observation and exploration conditions across participants and for all except one individual participant suggests that the methods used here were unable to identify consistent differences in

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cognition associated with active exploration of a simulation and observation of simulation output. This is an important finding and is discussed further below.

Table 1: Summary of t statistic comparisons of activation between conditions for each participant and across all participants (NSD=No significant difference)

Participant	Simulation Output during Observation versus Rest	Simulation Output during Exploration versus Rest	Simulation Manipulation during Exploration versus Rest	Simulation Output during Exploration versus Observation
1	Left occipital lobe, Left cerebellum posterior lobe, Right frontal lobe mid-frontal gyrus	Right parietal lobe, Right temporal lobe, Right frontal lobe mid-frontal gyrus	Right parietal lobe, Left parietal lobe	NSD
2	Right mid-frontal gyrus, Right frontal lobe pre-central gyrus, Left occipital lobe	Right parietal lobe, Left parietal lobe, Right occipital lobe	Right parietal lobe, Left parietal lobe, Right occipital lobe	NSD
3	Right parietal lobe, Right frontal lobe mid-frontal gyrus, Right temporal lobe	NSD	Right occipital lobe, Left occipital lobe	NSD
4	Left parietal lobe, Right parietal lobe	Left parietal lobe, Left temporal lobe, Right parietal lobe	Left parietal lobe, Left cerebellum posterior lobe, Right parietal lobe	NSD
5	Left occipital lobe, Right occipital lobe, Right frontal lobe mid-frontal gyrus	Right occipital lobe, Left occipital lobe, Left temporal lobe	Right occipital lobe, Left occipital lobe, Right frontal lobe mid-frontal gyrus,	Right frontal lobe superior frontal gyrus, Left frontal lobe superior frontal gyrus, Right parietal lobe, Left limbic node, parahippocampal gyrus
6	Left occipital lobe, Left cerebellum posterior lobe Right occipital lobe	Right occipital lobe, Left occipital lobe, Left cerebellum posterior lobe	Left occipital lobe, Left cerebellum posterior lobe, Left parietal lobe, Right occipital lobe	NSD
7	Right parietal lobe, Right occipital lobe, Left occipital lobe, Right frontal lobe mid-frontal gyrus	Right parietal lobe, Right occipital lobe, Left occipital lobe, Right frontal lobe mid-frontal gyrus	Right parietal lobe, Right occipital lobe, Left occipital lobe	NSD
8	Right parietal lobe, Right occipital lobe, Left occipital lobe	Right parietal lobe, Left occipital lobe, Right occipital lobe	Right occipital lobe, Left parietal lobe, Right parietal lobe	NSD
Second Level Across All Participants	Left frontal lobe pre-central gyrus Right frontal lobe mid-frontal gyrus Right parietal lobe	NSD	Parietal lobe	NSD

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Given the lack of consistent activation differences between the two conditions across all participants, and given the results of our other studies suggesting that there is wide variability in the strategies used during simulation exploration (see Dalgarno, Kennedy & Bennett, 2012), our focus has now shifted to exploring the results associated with individual participants to see whether the fMRI data can be used to complement other sources of data such as interaction log file data showing the exploration strategies used, learning outcome measures and levels of engagement as measured through engagement questionnaires, to provide a more complete picture of the learning process exhibited by participants. A full discussion of this is outside the scope of this paper but by way of illustration the fMRI results and learning processes of Participant 5 are discussed in the following paragraphs.

Participant 5 was the only participant for whom there were differential activations for all comparisons, including the comparison between activation when viewing the simulation output in the observation and exploration conditions. This participant undertook their observation condition using the global warming resource and their exploration condition using the blood alcohol concentration resource. Their pre and post test results suggested that they began with little understanding of the main concepts associated with either knowledge domain but achieved substantially improved scores in the post test indicating that they learned very effectively in both conditions.

For the first level analysis carried out using the data from Participant 5, the areas where significant differences were found are generally consistent with expectations. Activation patterns while viewing simulation output include increased activation in the occipital lobe and areas of the pre-frontal cortex and the temporal lobe compared to rest, suggesting that the participant was undertaking working memory organisation, long term memory storage and retrieval and visual information processing during these periods. Most interestingly the differential activation between viewing of simulation output in the exploration and observation conditions are consistent with the original hypothesis. Activation in the superior frontal gyrus of the right and left frontal lobes (part of the pre-frontal cortex) suggests greater working memory organisation and possibly greater activation of long-term memory storage and retrieval pathways in the exploration condition. The differential activation of the left parahippocampal gyrus within the limbic node also suggests that there may have been greater degrees of memory encoding and retrieval in this condition for this participant.

Future analysis of the data collected for this and other participants will be carried out to determine whether the measured activation provides a picture of the learning process consistent with the other data sources and whether the fMRI data adds to picture provided by the other data.

Discussion and conclusion

In relation to the research questions exploring the differences in brain activation between participants using a discovery-based and a tutorial-based instructional resource, the findings are somewhat equivocal, but suggest that there may be no consistent difference in activation. Clearly, more research is required to further refine the methodological approach used in the study, however, we believe that this result if replicated in other studies, has the potential to add to our understanding of the relationship between interactivity and cognition when using instructional software. Such a finding would be consistent with arguments by some researchers that an active learning process is not dependent on behavioural activity but on cognitive activity (see Alferi et al., 2011). Piaget himself warns that a common misuse of his ideas is “that which leads people to think that any ‘activity’ on the part of the student or child is a matter of physical actions, something that is true at the elementary levels but is no longer so at later stage, when a student may be totally ‘active’, in the sense of making a personal rediscovery of the truths to be acquired, even though this activity is being directed towards interior and abstract reflection” (Piaget, 1977; p. 714).

In relation to the broader feasibility of the use of functional brain imaging methods, specifically fMRI to address research questions associated with cognition and learning using instructional simulation software, a number of important methodological issues were encountered (see also Dalgarno, Kennedy & Bennett, 2010, for a more detailed discussion). A key issue was that in order to clearly separate out brain activation associated with different elements of the task (planning, manipulation and viewing of results) the software interface had to be designed in such a way that the participant was required to work through these aspects of the task in a lock step fashion. This meant that it was not possible to use existing instructional resources in the study. It also meant that the nature of the cognitive engagement and learning may to some extent have been different than would be expected if using conventional discovery-based resources which allow for less constrained exploration. Despite these restrictions, brain activations were inferred that were explainable by theory. Consequently the results are somewhat promising in terms of the applicability of these methods to this type of research problem.

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