Using fMRI to explore interactivity and cognition: A methodological case study

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Recent educational models of computer-based interactivity stress the important role of a learner's cognition. 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. Research methods that have been used to investigate cognition and learning have traditionally included self-report questionnaires, focus groups, interviews and think-aloud protocols and, more recently in computer-based settings, interaction log file or 'audit trail' analysis. 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. The use of functional brain imaging techniques has the potential to address this limitation. Drawing on issues encountered during a current study using Functional Magnetic Resonance Imaging (fMRI), this paper discusses the key methodological issues involved in the use of these techniques for exploring interactivity and cognition.

Keywords: interactivity, cognition, multimedia, functional brain imaging, fmri, learning

Introduction

This paper describes the methodological issues encountered during a current project exploring cognition and interactive multimedia using a combination of functional brain imaging and traditional behavioural and self-report measures. The paper begins with a discussion of the problem addressed and the traditional methods for exploring it. It is then argued that the addition of functional imaging methods has promise in addressing aspects of the problem. The research questions and research design in the current project are then explained, followed by a discussion of the methodological issues encountered during the project so far.

The problem

For nearly 50 years researchers have been investigating the design of Computer-Assisted Learning (CAL) resources and their contribution to learning. More recently Interactive Multimedia (IMM) resources have become a particular focus of this research. It is generally acknowledged that the key advantage such resources have over alternatives such as video, is the capacity for high levels of learner–computer interaction and engagement (Rieber, 2005). Many have observed that children and young adults are more easily engaged through the use of computer games than through any part of their formal education or schooling. Consequently, it is generally agreed that there is great potential for the use of interactive multimedia learning resources if similar levels of engagement to computer games can be achieved (Gros, 2003), and if tasks to be undertaken using the resources can be designed in such a way as to be authentic and aligned to the desired learning (Bennett, 2006; Dalgarno & Harper, 2004).

The high level of user–computer interactivity that occurs in computer games is central to the high degree of engagement facilitated by them. This interactivity has also been highlighted as a key feature of interactive multimedia resources that can lead to learning advantages. 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). Additionally, the value of active learning processes over passive alternatives has been well established (Jonassen, 1991; Piaget, 1973). 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 (Sims, 1997). More recently it has been acknowledged that any model of learner–computer interaction must incorporate cognition as a central element, or put another way the cognition that occurs through this interaction is of central importance in predicting the learning that will occur (Dalgarno, 2004; Kennedy, 2004).

Drawing on this body of prior research then, the aim of our current research is to discover how interactivity in multimedia environments impacts on users' cognitive processes and subsequent learning outcomes.

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; Ericsson & 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 appears to be value in also looking beyond these methods.

Alternative: The addition of functional brain imaging

An alternative approach to exploring cognition is to use functional brain imaging methods, such as Functional Magnetic Resonance Imaging (fMRI) or Positron Emission Tomography (PET), to identify the brain activation occurring during certain tasks. In recent years, with the increased availability of the equipment needed for these methods, the new field of *cognitive neuroscience*, which draws on physiological imaging techniques from neuroscience as well as behavioural techniques from psychology and theoretical approaches from cognitive science, has contributed to a range of problems previously explored only using behavioural methods (Churchland & Sejnowski, 2000; Gabrieli, 2005). Although functional brain imaging techniques have been used in neuroscience for more than 20 years, the widespread use of such techniques within psychology, cognitive science and education has only occurred within the last five to 10 years. There have, however, already been an enormous number of published studies. Consequently, the equipment, materials and procedures are now very well established and there are commonly accepted protocols for ensuring the safety and comfort of participants (see, for example, National Health and Medical Research Council, 2005).

Most of the research to date using functional brain imaging methods has focussed on the identification of brain regions activated while the participant undertakes a particular cognitive task (that is, with a goal of identifying the neural-correlates of these tasks). The tasks used are typically very basic, such as verbal memory tasks or simple problem solving tasks, such as the 'Tower of London'. This research has led to a large body of results associating brain areas with types of cognition. This large body of data can potentially be drawn upon in interpreting the results of functional imaging studies involving more holistic tasks, such as problem-based learning tasks using interactive multimedia. 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 it could be concluded that the interactivity contributes to retention. It is important to point out, however, that the cognitive neuroscience 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. For example, any task involving problem solving will typically also involve storage and retrieval of information from working memory and often also from long-term memory. Nevertheless, we believe that there is sufficient data available to allow conclusions to be drawn about the degree to which brain activation data is consistent or inconsistent with accepted theories of learning. This can be done by comparing the cognition implied by brain activation measured during the use of interactive multimedia with the cognition proposed by theory.

Overall research design and specific research questions

We are currently working on a pilot study addressing specific aspects of the relationship between interactivity, cognition and learning outcomes. The study involves a comparison of the cognitive processing and learning outcomes occurring through the use of two distinct types of multimedia program: a tutorial-based design and an interactive simulation-based design. In addressing this issue, we are using a combination of traditional methods with functional brain imaging methods. We have developed simulation-based and tutorial-based multimedia resources addressing two learning domains (global warming and blood alcohol concentration) and we are exploring cognitive processing and learning outcomes using the following data collection methods:

- written pre-tests and post-tests on declarative knowledge and conceptual understanding
- questionnaires on engagement and intrinsic motivation
- audit trail methods to explore behavioural interactivity
- stimulated response interviews involving the playback of the participant's recorded interactive session during an interview, in order to capture the participant's reflections on their own cognitive processing, and
- Functional Magnetic Resonance Imaging (fMRI) to measure brain activation.

The following specific research questions will be addressed by the study:

- Is there a detectable difference in the overall brain activation between users of a simulation-based and a tutorial-based multimedia learning resource?
- If so, does this difference explain predicted differences in the learning processes and outcomes of users interacting with these two types of resources?
- Is brain activation during identified interactive episodes (while using an educational multimedia resource) consistent with the cognition predicted by accepted theory?

Hypotheses

In order to identify brain activation differences expected between the simulation and tutorial-based conditions, it is necessary to first identify the differences in cognition predicted by theoretical and empirical research in educational technology and educational psychology. This research suggests that users of simulation-based multimedia would be expected to experience the following types of cognitive processing to a greater extent than users of tutorial-based multimedia:

- Deep *elaborative processing* and cognitive organisation and reorganisation of information, due to the requirement for the learner to regularly draw on their current understanding as they make decisions and attempt to predict how the simulated environment will respond in order to reach a task goal (see Craik & Lockhart, 1972; Wittrock, 1994; Norman & Schmidt, 1992).
- Greater degrees of self-reflection and *metacognitive self-monitoring*, as a result of observing the regular provision of *feedback* in the form of system responses to actions undertaken within the environment.

Drawing on research from cognitive neuroscience, we can then generate hypothesised brain activation associated with each of these types of cognitive processing. The following are some of the key associations:

- The *hippocampus*, the *dorsolateral prefrontal cortex (DLPFC)* and the *ventrolateral prefrontal cortex (VLPFC*) have been associated with elaborative processing and cognitive organisation (Fernandez & Tendolker, 2001; Gazzaniga, Ivry & Mangun, 2002; Blumenfeld & Ranganath, 2006; Prince, Daselaar & Cabeza, 2005);

- Feedback based learning has been found to result in activation of the *basal ganglia*, including the *striatum* and the *caudate nucleus* along with areas of the *prefrontal cortex (PFC)* and the *posterior frontomedian cortex (pFMC)* (Shahomy et al., 2004; Little et al., 2006; Volz, Schubotz & Yves von Cramon, 2005);
- Tasks requiring error detection and monitoring of activity and requiring choices to be made have been found to activate the *anterior cingulate cortex (ACC)* and where conflicting options are available, pFMC activation has been found (Elliot and Dolan, 1998; Ullsperger & Yves von Cramon, 2004);

An annotated diagram from *Scientific American* showing the main areas within the brain, including most of those mentioned above can be found in Graham (2006).

Imaging methods

The two most common brain imaging techniques, Functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET), provide an indication of the specific areas of the brain that are activated while a person is undertaking a particular task (Cabeza & Kingstone, 2001). FMRI involves the measurement of regional fluctuations in magnetic fields, which correlate with blood flow and in turn brain activation. The participant lies with their head and upper body inside the scanner, and with their head completely still (see Figure 1). A projected computer image is viewed via a mirror above the participant's head and interaction occurs using simple hand-held buttons or a special purpose mouse. Headphones and a microphone can be used to communicate with the participant, although subtle head movements associated with speech make it difficult to measure activation while the participant is talking (Huettel, Song & McCarthy, 2004). The cost ranges from about $A900 to about $A1500 per participant (Brain Research Institute, 2006).

Figure 1: A Magnetic Resonance Imaging (MRI) scanner (Brain Research Institute, 2006)

When using PET the participant is first injected with a tracer radionuclide. This tracer travels through the bloodstream and is metabolised within the brain, leaving a signature corresponding to blood flow to each brain region. Positrons are emitted during the decay of the tracer and these are detected during scanning. The two key alternatives for PET are short half-life, water-based, and long half-life, glucose based radionuclides. When using water-based radionuclides, which decay in a matter of minutes, the participant is repeatedly injected while they undertake tasks with their head inside the scanner. This approach to functional imaging is becoming quite rare because the costs and risks to the participant are greater than fMRI, while the type of data obtained is similar but is generally not as accurate. However, an alternative approach using longer half-life glucose based radionuclides has distinct advantages for some types of studies. Because the half-life of these radionuclides is over 100 minutes, the participant, after being injected, can carry out tasks on a computer outside of the scanner and undergo scanning once the task is complete. This technique allows the overall activation to be measured, rather than the activation at discrete moments during the task, but the ability to carry out tasks outside of the scanner leads to greater task authenticity and consequently greater external validity in the findings (Cabeza & Kingstone, 2001).

In our study we have chosen to use fMRI because of our interest in the brain activation occurring at discrete moments during an interactive session. Although water-based PET can also be used to gather this data, fMRI is less physically intrusive, involves less risk for the participant, provides greater temporal fidelity through more frequent scans, is more readily available and is less costly.

There are two common approaches to experiment design for functional imaging studies. The first is a *block design*, whereby a series of stimuli of a similar type are presented in a block. For fMRI the block length is typically about 30 seconds and there might be around 60 blocks of stimuli presented during the session. Activations can be compared across two or more stimuli or alternatively activation during the stimulus condition can be compared to activation during a regular *baseline* or rest condition. The alternative is an *event-related design*, where the participant's interactions define *events* which are categorised prior to analysis. Analyses in our study include comparisons of overall activation across the two conditions as well as the use of event-related methods to compare activation during identified categories of interactive task.

Multimedia design

Our original intention was to use an existing multimedia resource for the simulation condition. The resources we had in mind provided an interactive simulation as the central component, supplemented by text-based and graphical support materials. Such resources allow complete learner control over their exploration within the resource. Our intention was to produce a tutorial resource based primarily on the text-based and graphical supplementary material within the resource, structured in a lock-step sequence with control only over the pace that the information was presented.

As our understanding of fMRI methodology increased through discussions with experienced researchers along with extensive reading, we realised that to use our intended multimedia designs would result in an experimental design that departed substantially from accepted practice in fMRI research. The following were the key methodological problems with our intended approach:

- The complex physical interaction in the simulation condition could confound the results because it would be difficult to differentiate between brain activation associated with the motor tasks and brain activation associated with the cognitive task.
- The visual differences between the simulation and tutorial conditions could confound the results because it would be difficult to differentiate between the brain activation associated with attending to the rich multimedia content in the simulation condition from the activation associated with the cognitive task.
- It would be difficult to provide a regular baseline or rest stimulus within the simulation condition if we allowed complete learner control.

These constraints initially were a source of great frustration to us. We were very keen to use a simulation condition that was as authentic as possible so that the results obtained would be applicable to naturalistic settings. Having to decide on an appropriate compromise between internal and external validity is common in educational research using an experimental design. Greater control over variables normally increases the internal validity but decreases the external validity and thus the applicability of the findings to authentic settings. In this case, however, we initially felt that the compromises we would have to make would have too detrimental an effect on external validity. Upon further analysis, however, we came to the conclusion that an experiment with a great deal of control over the differences between the two conditions would provide us with some very important initial results. We also felt that carrying out our first fMRI study using a design somewhat similar to conventional fMRI studies would be sensible. Once we had developed greater knowledge of the methodological issues and analysis techniques we would be in a better position to consider departing from convention by using more holistic tasks and perhaps a greater degree of qualitative analysis of the brain activation data.

In addition to the methodological issues associated with our intended multimedia designs, we were also constrained by the fact that an MRI compatible mouse was not available to us. Because of the use of powerful magnets in MRI, it is unsafe to use any device that emits electromagnetic radiation in the scanner and consequently special purpose devices using optical rather than electrical signals are required.

An MRI compatible mouse has recently become available overseas but our budget did not allow us to purchase one and we were unable to find anybody using one in Australia. Consequently, it was necessary to develop new resources or substantially tailor existing resources so that they used a push-button interface.

Ultimately, we decided to develop our resources from scratch, although in one case we drew on an existing resource for the simulation model. Using Macromedia Director, we have developed four multimedia resources, a tutorial and a simulation resource in each of two learning domains. The domains chosen were global warming and blood alcohol concentration. These topic areas were chosen due to their mainstream interest, the fact that misconceptions exist about each, and our view that substantial learning was possible without a great deal of prerequisite knowledge. It was necessary to choose two learning domains because fMRI analysis must initially be carried out within subject, and thus it was necessary for each participant to use both a tutorial and a simulation resource. Within subject analysis is necessary because cerebral blood flow varies greatly across the population, and so absolute blood flow for one participant cannot be compared to absolute blood flow for another participant. To control for differences in complexity in the learning outcomes we decided to develop a tutorial and a simulation resource in each domain. With eight participants, this has allowed us to use a balanced design, controlling for order effects and domain complexity effects.

Screen images from the developed resources are shown in Figures 2, 3 and 4. The following are the key aspects of their design:

- Each resource is divided into two parts, a background section and a main section.
- The background section, common to the simulation and tutorial versions, consists of a series of screens containing background information about the problem domain. This information is not accessible once the participant moves to the main part of the resource but they can spend as much time reading this background information as they wish and they can move backwards and forwards through the screens within it.
- The main part of the tutorial and simulation versions has been designed with identical screen layouts, with the main part of the tutorial resource consisting of a series of output screens from the simulation, annotated with a text explanation but without the ability to control the simulation parameters.
- The simulation resource is structured so that participants plan their manipulations on one screen, carry out their manipulations on another, and view feedback on a third screen.
- Both the tutorial and the simulation resource contain a regular baseline or rest stimulus condition, consisting of random numbers and graphs and an animated highlight.
- In the tutorial resource, once the participant finishes reading the background information, they view a series of simulation output screens with the baseline screen displayed between each. In the simulation resource, once the participant finishes reading the background information, they view a repeated sequence of planning, manipulation, feedback and baseline screens.
- Interaction occurs through the use of a 4-button device. The resources have been programmed to use three of these buttons, with the left and right button moving a highlight forwards and backwards between options on the screen, and the middle button activating the highlighted option.

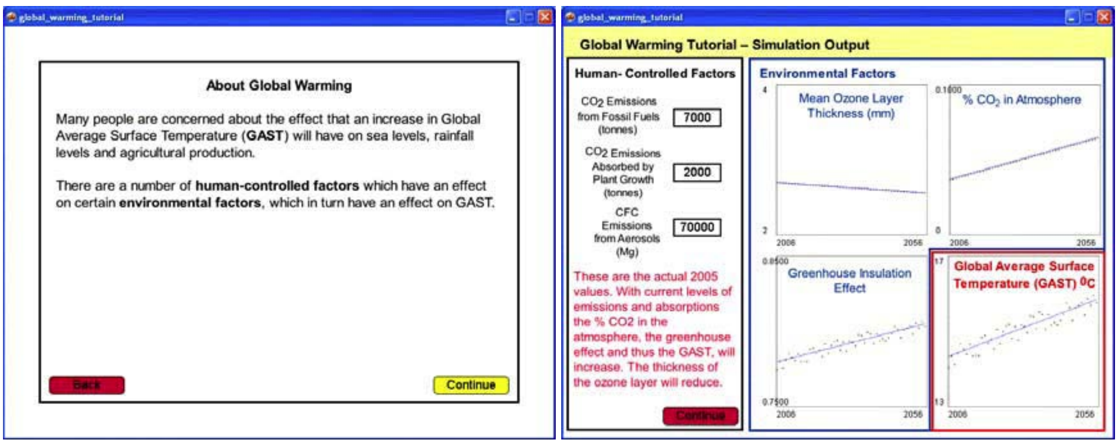

Figure 2: Example background screen from the global warming simulation and tutorial resources (left) and example simulation output screen within the global warming tutorial resource (right)

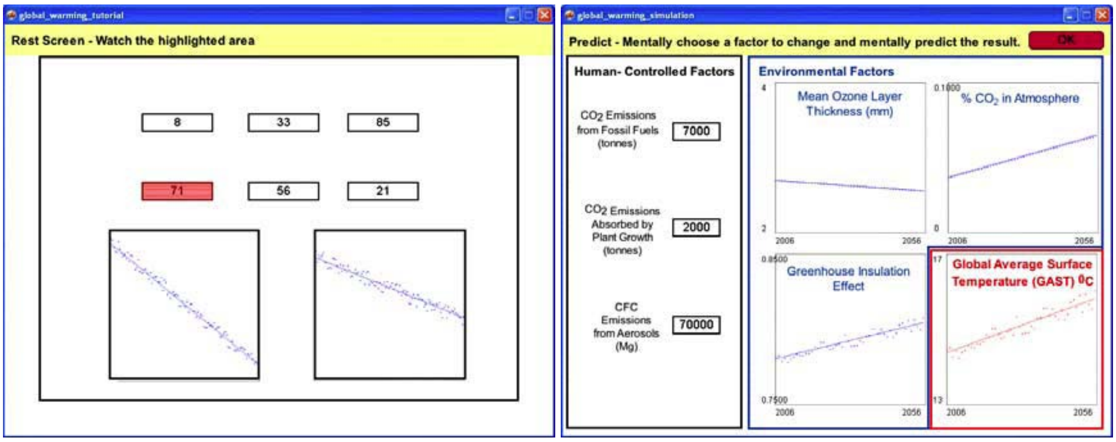

Figure 3: Example rest screen (left) and example planning screen from the global warming simulation resource (right)

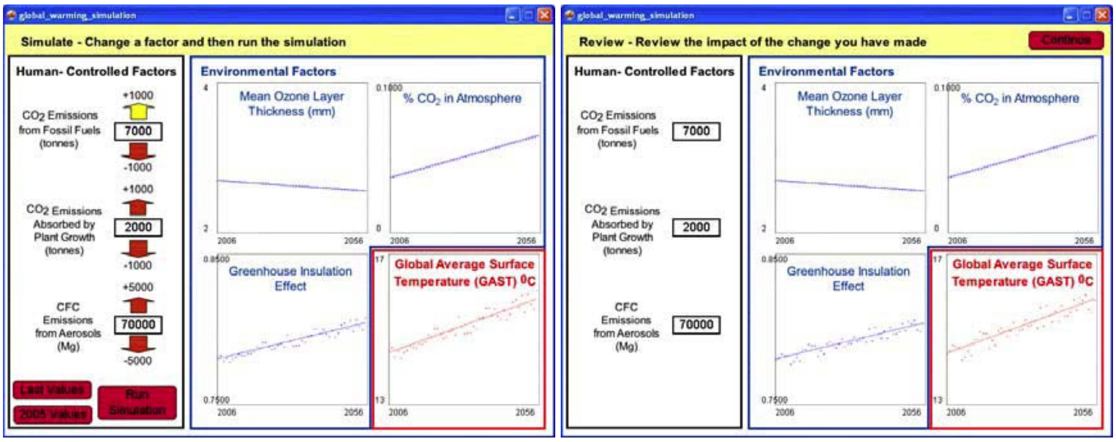

Figure 4: Example manipulation screen (left) and example feedback screen (right) from the global warming simulation resource

Pilot studies

We have undertaken two stages of pilot testing of the resources and research instruments without the use of fMRI and have so far undertaken one stage of pilot testing using fMRI. We are planning another stage of fMRI pilot testing before we undertake the main study. In the first pilot study, a single participant used the global warming simulation resource. The following are some of the key changes made as a result of this pilot:

- A back button was added to the introductory section because the participant indicated that she wanted to refer back to earlier sections.
- Explanatory information including an annotated example simulation output screen was added to the background section to resolve confusion about the values within the simulation and their units.
- An explicit goal of stabilising the global temperature was added to the instructions within the background section because it was found that when, about half-way through the task, the participant fixed on this goal, she became more directed in her exploration.
- More detailed explanations about what to do on each screen were added to the background sections because the participant initially found that expectations about what to do on each type of screen (planning, manipulation and feedback) were unclear.
- The movement of the highlight on the baseline screen was made random because the participant found herself trying to predict its movement and the resource was reprogrammed to run full screen because the participant began attending to the icons on the computer's desktop.
- Changes were made to the pre-test and post-test to address various ambiguities and limitations identified.

In the second pilot study two participants each used one simulation resource and one tutorial resource. The following are some of the key changes made to address issues that emerged during this pilot:

- Both participants found it difficult to organise their thinking in the intended way within the simulation resource. For example, one participant undertook her planning during each baseline screen and then skipped straight over each planning screen. To address this, a preparatory talk was developed, including the use of printouts of screen images, to help explain to participants how important it is that they organise their thinking according to the instructions provided.
- The scenarios in the blood alcohol tutorial were redeveloped to eliminate an identified bias towards male participants.
- Changes were made to the blood alcohol pre-test and post-test to address ambiguities and limitations identified.

In the first fMRI pilot study a single participant used the blood alcohol simulation while in the MRI scanner. It was our intention that this participant would also use the global warming tutorial resource and we also intended to have a second participant use the other two resources as part of the pilot. However, we encountered problems in the visibility of the screen from within the MRI scanner and decided instead to carry out a fourth pilot study after addressing this issue. Specifically, the participant initially found that she could not see the whole screen area through the mirror within the MRI scanner. When the projected screen area was reduced in size, she found that she could not read certain sections of text within the resource because the fonts were too small. The other problem that emerged during this pilot was difficulty with playing back the animated screen image captured using Camtasia Studio with sufficient control during the interview. Alternative video playback software is being explored with a view to using a package that allows rapid controlled scrolling through the recorded session.

Pilot testing of research protocols is essential in any research, but we found it particularly important in this research due to the innovative nature of the methods used. As well as using all of the various types of data gathering described above, we also asked additional interview questions in these pilot studies in order to evaluate the suitability of the multimedia resources and the various research instruments. We found these interviews particularly useful as a way of exploring the thinking process and learning approaches of the participants. The ability of the participants to follow the strategy implicit within the simulation resource designs, and in particular to carry out the various types of thinking at the right time, or while looking at the right screens, will be essential in analysing the brain activation data. We found that participants were not always able to follow our instructions in this respect, and as a result we have tailored the way we prepare our participants.

Next step: Analysis

The next stage in the project will be to analyse the data from the fMRI pilot study. The focus of this analysis will be an exploration of the blood flow (and thus activation) during the planning, manipulation and feedback screens relative to activation during the baseline screen. The analysis process requires the use of specialised software. We will be using a package called Statistical Parametric Mapping (SPM), a set of library routines or plug-ins for MatLab. The following is a summary of the main steps that have to be carried out in the analysis:

- The data is run through a motion correction algorithm to correct the data during periods when the participant's head was not absolutely still.
- The data is then run through a slice timing correction algorithm to adjust for the fact that it takes around 3 seconds for a complete image to be acquired, during which there may be changes in activation.
- Temporal filtering is then carried out to correct for low frequency changes in blood flow during the session, for example changes associated with the participant's mood changes.
- The data is then transformed to a 'standard' brain map to allow for differences in the size and shape of participants' brains to be taken into account when comparing activations across participants.
- The time-codes of each 'block' of stimuli or each 'event' are then specified (in our case, the time-codes when the participant moves from one screen to another).
- A General Linear Model (GLM) is then fitted to the data to determine whether there are statistically significant differences in activation between conditions.

In analysing the data for the first fMRI pilot, we are expecting to find activation of brain areas associated with planning, decision making and cognitive organisation corresponding with periods when the participant was on the planning screen, and activation of brain areas associated with feedback, error detection, and elaborative processing corresponding with periods when the participant was on the feedback screens. If such activations are able to be identified, this will give us confidence that our multimedia resources and task instructions are appropriate as we move towards the final fMRI pilot. The data from the final fMRI pilot will be analysed to determine whether there are detectable differences between activation during the tutorial-based and simulation-based conditions. We will then be ready to commence the main study.

Conclusion

This paper has described the methodological issues encountered during a study involving the use of fMRI along with traditional behavioural and self-report measures to explore the cognitive processing occurring while using a simulation-based and a tutorial-based multimedia resource. Although findings in relation to the research questions are not yet available, substantial development in our understanding of the methodological issues has occurred. We began the project with a degree of healthy scepticism. Our findings to date suggest that there certainly are some important limitations in the types of learning tasks that can be explored using fMRI and thus the types of questions that can be addressed. Despite this, we feel that the area has great promise and that with appropriate experimental design it will be possible to develop a deeper understanding of cognition and interactivity through the use of fMRI in conjunction with traditional methods than would be possible through traditional methods alone.

References

Bennett, S. (2006). Using related cases to support authentic project activities. In A. Herrington & J. Herrington (Eds.), *Authentic Learning Environments in Higher Education* (pp. 120–134). Hershey, PA: Idea Group Inc.

Blumenfeld, R. S., & Ranganath, C. (2006). Dorsolateral prefrontal cortex promotes long-term memory formation through its role in working memory organization. *Journal of Neuroscience*, *26*(3), 916–925.

Brain Research Institute (2006). The Brain Research Institute, Melbourne, Australia. Retrieved July 21, 2006, from http://www.brain.org.au

Cabeza, R. & Kingstone, A. (2001). *Handbook of functional neuroimaging of cognition*. Cambridge, MA: MIT Press.

Churchland, P. S., & Sejnowski, T. J. (2000). In M. S. Gazzaniga (Ed), *Cognitive Neuroscience: A Reader* (pp. 14–24). Malden, Mass: Blackwell.

Craik, F.I.M. & Lockhart, R.S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behaviour*, 11, 671–684.

Dalgarno, B. (2004). A classification scheme for learner–computer interaction. In R.Atkinson, C.McBeath, D. Jones-Dwyer and R.Phillips (eds) *Beyond the comfort zone, 21st annual conference of the Australasian Society for Computers in Learning in Tertiary Education,* (pp. 240–248). Perth, Australia.

Dalgarno, B. and Harper, B. (2004). User control and task authenticity for spatial learning in 3D environments. *Australasian Journal of Educational Technology*, 20(1), 1–17

Elliott, R. & Dolan, R.J. (1998). Activation of different anterior cingulate foci in association with hypothesis testing and response selection. *NeuroImage*, 8(1), 17–29.

Ericsson, K. A., & Simon, H. (1993). *Protocol analysis: verbal reports as data*. Cambridge, MA: MIT Press

Fernández, G. & Tendolkar, I. (2001). Integrated brain activity in medial temporal and prefrontal areas predicts subsequent memory performance: Human declarative memory formation at the system level. *Brain Research Bulletin*, 55(1), 1–9.

Gabrieli, J. (2005). *Educating the Brain: Lessons from Brain Imaging*. Retrieved August 29, 2005, from http://www.educause.edu/content.asp?page_id=666&ID=FFP0510S&bhcp=1

Gazzaniga, M.S., Ivry, R.B. & Mangun, G.R. (2002). *Cognitive neuroscience: The biology of the mind*. W.W. New York: Norton & Company.

Graham, B. (2006). *Computing and the Brain*. Retrieved July 21, 2006 from www.cs.stir.ac.uk/courses/31YF/Notes/Notes_OV.html

Gros, B. (2003). The impact of digital games in education. *First Monday*, 8(7).

Huettel, S.A., Song, A.W., & McCarthy, G. (2004). *Functional Magnetic Resonance Imaging*. Sunderland, Mass: Sinauer Associates Publishers.

Jonassen, D. H. (1991). Objectivism versus constructivism: Do we need a new philosophical paradigm? *Educational Technology Research and Development, 39*(3), 5–14.
Kennedy, G.E. (2004). Promoting cognition in multimedia interactivity research. *Journal of Interactive Learning Research,* 15(1), 43–61.
Kennedy, G.E. & Judd, T.S. (2004). Making sense of audit trail data. *Australasian Journal of Educational Technology, 20* (1), 18–32.
Little, D.M., Shin, S.S., Sisco, S.M. & Thulborn, K.R. (2006). Event-related fMRI of category learning: Differences in classification and feedback networks. *Brain and Cognition*, 60(3), 244–252.
Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. Thousand Oaks, CA: Sage.
National Health and Medical Research Council . (2005). *Human Research Ethics Handbook: Research Involving Radiation*. Retrieved August 26, 2005 from http://www.nhmrc.gov.au/publications/hrecbook/02_ethics/35.htm
Norman, G.R. & Schmidt, H.G. (1992). The psychological basis of problem-based learning: A review of the evidence. *Academic Medicine*, 67(9), 557–565.
Piaget, J. (1973). *To understand is to invent: The future of education*. New York: Grossman Publishers.
Prince, S. E., Daselaar, S. M., & Cabeza, R. (2005). Neural correlates of relational memory: Successful encoding and retrieval of semantic and perceptual associations. *Journal of Neuroscience*, *25*(5), 1203–1210
Rieber, L.P. (2005). Multimedia learning in games, simulations and microworlds. In R.E.Mayer (Ed), *The Cambridge Handbook of Multimedia Learning*, New York: Cambridge University Press.
Shohamy, D., Myers, C. E., Grossman, S., Sage, J., Gluck, M. A., & Poldrack, R. A. (2004). Cortico-striatal contributions to feedback-based learning: Converging data from neuroimaging and neuropsychology. *Brain*, *127*(4), 851–859.
Sims, R. (1997). Interactivity: A forgotten art? *Computers in Human Behaviour*, 13(2), 157–180.
Ullsperger, M. & Yves von Cramon, D. (2004). Neuroimaging of performance monitoring: Error detection and beyond. *Cortex,* 40(4–5), 563–604.
Volz, K.G., Schubotz, R.I., Yves von Cramon, D.Y.(2005). Frontomedian activation depends on both feedback validity and valence: fMRI evidence for contextual feedback evaluation. *NeuroImage*, 27(3), 564–571
Wittrock, M.C. (1994). Generative Science Teaching. In P.J. Fensham, R.F. Gunstone and R.T. White (eds), *The Content of Science*, (pp. 29–38). London: The Falmer Press.

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