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Can functional brain imaging be used to explore interactivity and cognition in multimedia learning environments?

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Abstract

This paper reviews existing methods used to address questions about interactivity, cognition and learning in multimedia learning environments. Existing behavioural and self-report methods identified include observations, audit trails, questionnaires, interviews, video-stimulated recall, and think-aloud protocols. The limitations of these methods are examined, highlighting the problems with using behavioural information to speculate about the cognitive activity that is occurring; the difficulties posed by relying on the correct interpretation of questions or accurate recall of past events; and the potential for the data collection methods to have an impact on cognition as it is occurring. Functional brain imaging techniques offer a complement to the existing methods, but possess a number of inherent methodological constraints. The specific constraints emerging from a recent pilot study which developed and tested a methodology appropriate to educational studies are discussed in detail, including: limitations on learner-computer interaction because of the need to use MRI compatible input devices; activation from motor tasks potentially confounding the results of comparisons between cognition occurring during interactive and non-interactive resources; visual differences between multimedia conditions potentially confounding the results due to activation associated with the visual processing; and problems with the provision of 'baseline' or 'rest' conditions for comparison purposes during holistic problem-based tasks. Despite these constraints it is argued that the use of functional imaging techniques within this field of research has significant potential.

Keywords

Interactivity, Cognition, Learning, Multimedia, Functional brain imaging, fMRI, Research methods

Introduction

The potential for interactive multimedia to enhance learning has generated enormous interest over the past 10 to 15 years. This has been driven by the advent of the personal computer and the subsequent rise of computer-supported learning. In the early 1990s computing became sufficiently powerful to combine text, graphics, animation, audio and video in a single software program – this became known as 'interactive multimedia'. At the same time, authoring tools were developed to support the creation of interactive multimedia, and CD-ROM technology provided a means to distribute multimedia software. This wave of technical innovation created a major shift in educational technology as interactive multimedia was hailed as the latest solution to educational problems.

Early questions about interactive multimedia focused on issues such as: how multiple media should be combined to present content (eg. which media should be used and how elements should be arranged on the screen); how multimedia information might be structured (linearly, hierarchically, Web-like etc.); 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 (e.g. Alessi & Trollip, 1985; Schwier & Misanchuk, 1993). Early interactive multimedia software generally took the form of programmed instruction as tutorial materials in which information was structured for the learner to work through logically and sequentially or as drill-and-practice activities to give learners an opportunity to perfect their responses with immediate feedback from an endlessly patient tutor (the computer). Limited choice was available to learners using this kind of 'prescriptive' software (Schwier & Misanchuk, 1993), based as it was on instructional design principles with their roots in behaviourist theories of learning (e.g. Gagne & Briggs, 1974). Although the range of interactive multimedia has expanded over time, this type of learning program is still widely available, perhaps best typified by much of the literacy and mathematics software available for young children.

Alternative types of multimedia software emerged with the development of interactive learning environments that went beyond simple instructional programs. *Investigating Lake Iluka* (Harper, Hedberg & Brown, 1995) was one of the first to apply the concept of an 'information landscape' (Florin, 1990), which recognised that learners can benefit when content is accessed through a metaphorical context, in this case through the ecology of a lake environment. *The Jasper Woodbury* series (Cognition and Technology Group At Vanderbilt, 1992), a learning environment developed for videodisc rather than CD-ROM, was influential in the emergence of inquiry-based learning software such as *Exploring the Nardoo* (Harper & Hedberg, 1997) and *Bioworld* (Lajoie, 2001). These packages differed from earlier forms of interactive multimedia in that they were not merely collections of information or a series of pre-determined lessons. Instead learners were presented with problems which they could solve using the resources available on the CD-ROM. Information was provided in a variety of media formats and genres to enhance the authenticity of the context represented. For example, *Exploring the Nardoo* contained scientific data, video news clips, and a botanical database as some of the information sources available to solve water conservation problems. 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.

The advancement of networked computing has quickly brought about mainstream access to the Internet and the World Wide Web. Initially communication and collaboration were the dominant forms of interaction afforded by this new medium, due largely to limitations associated with connection speeds and bandwidth. However, as bandwidth has improved interactive multimedia has increasingly become available online. This has greatly broadened the availability of interactive multimedia programs and resources in educational contexts. One example of this is *The Learning Federation Schools Online Curriculum Initiative*, which was established to develop and deliver multimedia online content to Australian and New Zealand schools (The Learning Federation, 2007). Whereas once educators and students were reliant on videodisc, floppy disk or CD-ROMs for the delivery of stand-alone interactive multimedia applications, now a wide range of educational applications, resources and tools is available through the internet.

Another development has been the advent and widespread use of highly engaging computer games, leading some to propose that game-like elements be included in educational multimedia (e.g. Gros, 2003; Rieber, 2005). Additionally, the developments in standard computer hardware and software driven by the games industry have opened up possibilities for designers and developers of educational multimedia that were unimaginable a decade ago. To date there have been few examples of educational multimedia incorporating the rich 3D graphics and the intense engagement of computer games but the future potential is substantial.

This brief history demonstrates that, despite changes in technology over the past decade, interactive multimedia remains relevant. However, educational technology researchers' understanding of the role interactivity plays in learning is limited. While there has been considerable discussion of how interactive learning environments should be designed, much of the literature reports broad instructional design models and principles rather than detailing the nature of the cognition and learning associated with interactive tasks in these complex environments (eg. Herrington & Oliver, 2000; Reigeluth, 1999; Jonassen, 1997).

This paper encourages educational technology researchers to renew their focus on interactivity as a fundamental construct. It discusses the possibility of a new avenue of interactivity research which brings together educational and psychological research traditions with the emerging field of cognitive neuroscience. The paper begins with an examination of the construct of interactivity. This is followed by a review of current methodologies for investigating the relationship between interactivity and cognition, and a critical discussion of new methods for investigating cognition using functional brain imaging.

Interactivity and cognition

While 'interactivity' is generally perceived by educators as a beneficial characteristic of multimedia environments, researchers have had some difficulty defining exactly what it is. Traditionally interactivity has either been described as the relationship between a computer program and the user, for example, Thompson and Jorgensen's (1989) reactive-proactive continuum, or defined by the functional affordances of a program's interface, as exemplified by Sims' (1997) developers' classification. Both these conceptions see user control and adaptivity as central to interactivity which is regarded as a dynamic relationship between two entities, either the user and the instructional source or the user and the interface (Kennedy, 2004).

While some early interactivity theorists recognised the need to consider what students were thinking (Jonassen, 1988; Hannafin, 1989), to a large extent this has been absent from discussions about the construct. More recently researchers have stressed that the internal cognitive processes of users are a fundamental component of interactivity (e.g. Aldrich, Rogers & Scaife, 1998). For example, Aldrich and colleagues (1998) argued that previous conceptions of interactivity inadequately addressed users' 'engagement' with the learning material or learners' 'internal' processes.

Kennedy (2004) further emphasised the lack of attention cognition has received in interactivity models and proposes a model of multimedia interactivity with three fundamental components: instructional events, users' behaviours, and users' cognitive processes. He suggested that, "Cognitive interactivity describes a continuous, dynamic relationship between instructional events and students' cognitive processes that is mediated by their behavioural processes" (p. 58). As such, this model places learners' cognitive processes at the heart of multimedia interactivity. This conception of interactivity is similar to Dalgarno's (2004) description and taxonomy of 'cognitive tasks' associated with learner-computer interactions. Here any specific task a learner carries out in a multimedia environment (e.g. selecting hypertext, manipulating variables in a simulation, etc.) carries with it both the nature of the task and the user's intent or motivation behind carrying out that task.

One of the primary benefits of creating interactive learning environments is that they help students to develop a fuller and deeper understanding of the material presented (see Kennedy, 2004). Foundational educational research on levels or 'depth' of processing and students' approaches to learning (Craik & Lockhart, 1972; Marton & Säljö, 1976) suggests that the cognitive strategies students use when they are learning directly impacts on the quality of their learning outcomes. For example, Craik and Lockhart (1972) proposed that stimuli are more memorable if they are processed at a 'deeper level'. Deep cognitive processing is reflected by 'elaboration coding', during which the stimulus is associated or related to prior knowledge. When applied in an educational context, the implication of Craik and Lockhart's view is that instructional material is more memorable when it is processed more deeply due to the cognitive strategy of elaboration. Given this, it could be argued that interactive learning environments that explicitly or implicitly promote the use of cognitive strategies such as elaboration, organisation and self-monitoring (see Weinstein & Mayer, 1986) will foster greater conceptual understanding.

A major focus of research on multimedia learning environments to date has been on the ways in which different design approaches impact on students' learning outcomes. In some cases the emphasis has been on the design of holistic learning tasks and the students' learning processes, and in others the focus has been on the presentation and organisation of multimedia content (e.g. Bennett, 2006; Brickell, Ferry, Hedberg & Harper, 2001; Cognition and Technology Group at Vanderbilt University, 1992; Herrington & Oliver, 1999). The qualitative case study and design research methodologies adopted in these types of studies have been particularly useful in discovering some of the design principles and conditions that lead to effective learning with interactive multimedia. Typically, these studies investigate small-scale complex learning situations in naturalistic settings over extended periods of time. While these studies have contributed to an understanding of the general patterns of cognition for specific learners within naturalistic settings they have not attempted to isolate and study the particular forms of interactivity inherent in particular learning resources nor the cognition associated with students' interactions.

Experimental research has also considered how interactive multimedia can be constructed to facilitate students' learning. The work of Richard Mayer and his colleagues has been instrumental in its contribution to an understanding of the way media elements can be combined within a presentation to facilitate learning (see Mayer, 2001). Based on the results from a considerable number of experimental studies, Mayer (1999) presented a series of design principles for educational multimedia drawing on information processing models of cognition. These studies primarily focussed on the way in which content material can be presented in order to maximise the ability of the learner to effectively process and store the information.

Using similar methods to those used in Mayer's studies, Sweller, van Merrienboer and Paas (1998) carried out a series of studies addressing the issue of cognitive load in the presentation of instructional information, focussing specifically the demands on working memory. For example, these researchers found that learners experience increased cognitive load when they have to refer to two or more distinct information representations, such as a picture and a separate caption. This research suggests that if the various sources of information can be integrated, the demands on working memory would be reduced leading to a consequential reduction in cognitive load.

Some of Mayer's later work began to explore the value of interactivity more directly (Mayer & Chandler, 2001; Mayer, Dow & Mayer, 2003; Moreno & Mayer, 2005). For example, Mayer and Chandler (2001) explored how giving students control over the pace of a narrated animation impacted on their learning. They found that students with control performed better on learning transfer tasks than students who received the same presentations without control. In another study, Moreno and Mayer (2005) explored the value of interactivity in a game-based multimedia environment. Interactivity was operationalised by asking students to choose solutions to problems they were presented with as opposed to the multimedia program simply presenting the solution to them. Moreno and Mayer (2005) found no differences between the two groups on measures of retention, and they reported marginal but significant differences for ‘close-transfer’ tasks in the unexpected direction (i.e. the groups using the non-interactive version scored higher than those able to make a choice of solution). However, for scores on ‘far-transfer’ students using the interactive version of the program scored significantly higher than students using the non-interactive version. While the results from these studies are somewhat equivocal, they do suggest that control-based interactivity promotes deeper cognitive processing which results in improved learning.

While not explicitly targeting interactivity and cognition, Cordova and Lepper’s (1996) study of students’ intrinsic motivation also has clear implications for this area of research. Using a computer-based mathematics learning game, these researchers manipulated the quality of the background or contextual information, the degree of individual personalisation and the amount of choice given to students. Their results showed that students who had more contextual information, had their learning experience individually tailored and had more choice “exhibited significantly higher levels of task involvement, as evidenced by their preference for more challenging versions of the game, their greater use of complex operations, and their emphasis on strategic play… ” (p. 725). In addition, these students performed significantly better in a post-test than students from other conditions.

Finally, some researchers have put forward conceptions of ‘interactive multimedia’ that go considerably further than user-controlled presentation of information. For example Rieber (2005) reviewed empirical research that had investigated the educational benefits of three types of interactive multimedia environments – games, simulations and microworlds – and drew general conclusions about how they could be effectively constructed (e.g. to provide users with graduated challenges and instructional support in open-ended discovery environments). In this review, Rieber (2005) alluded to the power interactive multimedia has for promoting elaborative cognitive processing, suggesting of simulations that, “When designed well, a user has many opportunities to build strong referential connections between both explanatory and experiential representations of the concepts and principles being modelled …” (p. 562). There is a need for research that begins with this standpoint on the value of interactive multimedia and explores the relationship between the design of the resource, the tasks undertaken by the learner, and the cognition and learning that occurs as a result.

Methodological limitations of previous interactivity and cognition research

The results obtained from the experimental and review studies outlined above are particularly useful in informing the design of educational multimedia. However, there are two reasons why such studies provide a limited contribution to our understanding of the relationship between interactivity and learners' cognitive processes. First, the experimental studies typically compare students' learning outcomes – their ability to recall or apply knowledge – after learning using differing multimedia designs. Although the results are typically explained in cognitive terms that include, for example, the demands on working memory or cognitive processing, few of these studies attempt to directly explore the learner's cognitive processing while using the resource. This point is acknowledged by Mayer (2001) who says of his extensive research program: "Although no direct measures of cognitive processing during learning were taken, students' problem-solving transfer performance was used as an indirect measure of constructivist learning" (p. 616).

The second reason why these studies offer an incomplete insight into cognition and interactivity is that, rather than focusing on interactivity per se, most consider how multiple representations of content can be most effectively presented to users. When researchers do go beyond the presentation of content, the conception of interactivity employed is somewhat impoverished. Interactivity is equated with students' ability to control the pace or order of the multimedia presentation (e.g. Mayer & Chandler 2001; Mayer, Dow & Mayer, 2003) or with their ability to select alternative responses from a list (e.g. Moreno & Mayer, 2005). These forms of interactivity seem quite simple when compared to, for example, the interactivity involved in exploring, manipulating and experimenting within a simulated environment (e.g. Rieber, 2005).

These two limitations indicate the need for empirical research that more directly explores the relationship between interactivity, cognition and learning. Such investigations would assess how interactive learning tasks affect students' cognitive processing within multimedia environments and as such would provide useful data for both researchers of student learning and multimedia designers. Research methods that can *directly* explore learners' cognitive processing as they interact with educational multimedia will help to address fundamental questions about how different interactive tasks can promote particular types of cognitive activity to promote an optimal set of learning outcomes.

Traditionally psychologists and educators have explored cognition and learning using questionnaires and written tests, interviews and observation (Miles & Huberman, 1994). In educational technology and human-computer interaction research these have been supplemented by the use of 'think-aloud protocols' (Ericson & Simon, 1993) and interaction log file or audit trail analysis (Kennedy & Judd, 2004). Another related technique is the use of video-stimulated recall (Lyle, 2003), in which participants' interactive sessions are recorded and then played back to them as stimulus during an interview. All of these techniques help researchers to understand students' learning process, but suffer from a number of inherent limitations, such as using behavioural information to speculate about the cognitive activity that is occurring (observation and audit trails), relying on the correct interpretation of questions or accurate recall of past events (questionnaires, interviews, video-stimulated recall, think-aloud protocols), or impacting on cognition as it is occurring (think-aloud protocols) (see Schwarz, 1999).

We contend that important questions relating to the way that students learn using interactive multimedia have not been fully addressed by previous research and, in many ways, cannot be completely accommodated by traditional research methods. The following section introduces functional brain imaging, an additional research method that could be usefully employed to address these questions, and the final section of this paper discusses conceptual and practical issues associated with employing imaging techniques effectively in pursuit of this goal.

Functional brain imaging

An alternative approach to exploring cognition is to use functional brain imaging methods to identify the areas of the brain that are active or stimulated during certain tasks (Cabeza & Kingstone, 2001). Although functional brain imaging methods have been used in neuroscience for more than 20 years, there has been a substantial increase in availability and affordability of the required equipment within the last 5 to 10 years. This has led to the emergence of a new field, *cognitive neuroscience*, which draws on physiological imaging techniques from neuroscience, behavioural techniques from psychology, and theoretical approaches from cognitive science. This field has contributed to a range of problems previously explored only using behavioural methods (Churchland & Sejnowski, 2000). Another consequence of the expansion in use of these techniques is that the protocols for ensuring the safety and comfort of participants are now well established (see, for example, National Health and Medical Research Council, 2005).

A great deal of the research to date using functional brain imaging methods has focussed on identifying brain areas that are activated when the participants undertake particular cognitive tasks, with an overarching goal of identifying the neural-correlates of these tasks. For example, studies have identified parts of the brain associated with motor-control of each part of the body, with processing of visual, auditory and other sensory information, and with numeric calculations, face recognition and language processing. The behavioural tasks that participants are asked to perform in these studies tend to be designed around very narrow cognitive tasks, in order to provide clear information about the association between categories of cognitive task and areas of the brain. For example, behavioural tasks include noting whether a face is familiar or unfamiliar, performing simple addition, or solving a structured problem such as the 'Tower of London' problem (e.g. Kaller et al., 2004). The results of such neural-correlate studies for individual patients as well as the aggregated results from a large number of these studies have been used in a range of clinical applications, such as to help surgeons predict the consequences of removing brain lesions or tumours, and to diagnose various types of brain disorders (Matthews, Honey & Bullmore, 2006). More broadly, such studies have contributed to our understanding of the brain as a system.

The other prominent area of research using functional imaging techniques has been research that has compared brain activations of participants with certain deficits or syndromes and normal participants, or has compared brain activations between participants with differing age, gender or cultural background. Like the first class of studies, this body of research has tended to use relatively narrow, structured tasks. For example, studies have explored the unique brain activation patterns associated with autism (Shreeve, 2005); the phonological deficits associated with dyslexia (Goswami, 2004); and the unique brain activation patterns of the mathematically gifted during spatial manipulation (O'Boyle et al., 2005).

The potential application of functional brain imaging methods in interactive multimedia research would be quite different to these two classes of studies. Rather than exploring the brain activation associated with very specific cognitive tasks, such research would make use of more holistic behavioural tasks and would use the brain activation data to help identify the range of cognitive processes carried out by the participant to complete the task. In order to do this research it would be necessary to draw on the large body of established findings from neural-correlate studies in the interpretation process. That is, by measuring the brain activation of participants undertaking interactive multimedia learning tasks, patterns of activation associated with certain types of interaction would be identifiable. By drawing on research that has established an association between narrow cognitive tasks and the activation of specific brain areas, an understanding of the cognitive processing that typically occurs during different types of interaction could be fostered. 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 a non-interactive task, then it could be concluded that the interactivity contributes to retention.

There have been few studies employing functional brain imaging to explore the brain activations occurring while using interactive multimedia. Almost all have used multimedia as a stimulus condition to facilitate very specific types of cognitive processing in order to explore the brain areas associated with these tasks. For example, Mcguire et al. (1998) used Positron Emission Tomography (PET) scanning while participants explored a virtual environment and identified brain areas associated with encoding object locations. Similarly, Baumann (2005) carried out a study in which participants navigated through a virtual apartment while undergoing functional Magnetic Resonance Imaging (fMRI) , identifying areas of the frontal lobe associated with levels of task loading, and Shelton and Gabrieli (2002) used fMRI while participants explored a virtual environment and identified differences in activation associated with the acquisition of route-oriented and survey-oriented spatial knowledge.

There have been even fewer fMRI studies using holistic learning tasks to explore the cognitive processes associated with instructional strategies in general, despite the fact that a number of researchers have argued for the value of such studies. For example, Gabrielli (2005) suggests that the ability to create images of the brain activity of learners holds tremendous potential. He goes on to say that "…indeed, we are close to uncovering what will arguably be valid alternatives to testing for measuring the efficacy of various teaching methods" (p.46). One of the challenges in interpreting the results of studies using more holistic tasks comes from the insufficient number of neural-correlate studies that identify a clear one-to-one relationship between a single cognitive function and single a brain area. Many neural-correlate studies have found that cognitive tasks 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 involve storage and retrieval of information in working memory (activating areas of the prefrontal cortex), and long-term memory (activating areas of the prefrontal cortex and areas of the medial temporal lobe including the hippocampus).

A consequence of the lack of clear one-to-one relationships between cognitive function and brain area is that measured activation of a specific brain area during a holistic task will not on its own allow conclusions to be drawn about the cognitive functions being performed during the task. Nevertheless, there is sufficient data available to allow conclusions to be drawn about whether or not the measured brain activation data supports a specific theory of learning. For example, if the learning theory suggests that the learner will experience greater cognitive load during a particular instructional condition, then increased activation of areas of the brain associated with working memory would be consistent with this theory. The feasibility of research studies using holistic tasks in this way will be discussed in more depth in the following section. First, however, the functional brain imaging technologies that are available and the methodological issues associated with them will be explored.

The most commonly used technology for functional brain imaging is functional magnetic resonance imaging (fMRI). 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 (see Figure 1). 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. Headphones and a microphone can be used to communicate with the participant, although this is avoided during scanning because subtle head movements associated with speech make activation difficult to measure while the participant is talking (Huettel, Song & McCarthy, 2004). The loud noise emitted by the machine during scanning can have an impact on the participant's concentration, but this can be reduced to some extent using headphones.

Figure 1.
A Magnetic Resonance Imaging (MRI) Scanner
(Brain Research Institute, 2006)

Prior to the widespread availability of fMRI many functional brain imaging studies were undertaken using positron emission tomography (PET). PET scanning involves the measurement of positrons emitted during the radioactive decay of a tracer radionuclide. The participant is first injected with this tracer, which travels through the bloodstream and is metabolised within the brain, leaving a signature corresponding to blood flow to each brain region. This approach to functional imaging is becoming quite rare for a number of reasons. The need to produce the tracer radionuclide on the premises substantially increases the costs involved and the risks to the participant are greater than fMRI because of the radiation involved. Additionally, because a whole brain MRI activation scan can be captured in as little as three second compared to minutes for a PET scan, fMRI has much greater temporal fidelity and allows a much greater number of data points to be gathered. A consequence of these issues is that almost all activation studies now use fMRI rather than PET.

In order to explore in more depth the feasibility of using fMRI in interactive multimedia research, the following section discusses the methodological issues encountered during a pilot study recently undertaken by the authors.

Using fMRI in interactive multimedia research: A case study

Background

A pilot study employing brain imaging, completed recently by the authors, addressed specific aspects of the relationship between interactivity, cognition and learning outcomes. The study involved a comparison of the cognitive processing and learning outcomes achieved through the use of two distinct types of multimedia program, one with a tutorial-based design and the other with an interactive simulation-based design. The overall research design of this pilot study is described in the following section, followed by a discussion of the key issues encountered with the use of fMRI methods in the study. A more detailed description of the study can be found in Dalgarno, Kennedy & Bennett (2006).

Research design

The purpose of the pilot study was to design and test a methodology appropriate to addressing the following research questions:

- 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?

Cognition and learning theory suggests that, compared to users of tutorial-based multimedia, users of simulation-based multimedia 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 simulation users would be expected to show greater activation in areas of the brain associated with information manipulation and long-term memory storage and retrieval, compared to tutorial users. Such areas include the prefrontal cortex, especially the dorsolateral and ventrolateral areas, and the medial temporal lobe, especially the hippocampus (Fernandez & Tendolker, 2001; Blumenfeld & Ranganath, 2006; Prince, Daselaar & Cabeza, 2005).

The 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 type of stimulus material (simulation-based and tutorial-based) were explored using a range of data collection methods, including written pre- 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, in order to explore the participant's reflections on their own cognitive processing; and functional Magnetic Resonance Imaging (fMRI) to measure brain activation.

There are two common experimental design approaches in 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*, in which the participant's interactions define *events* which are categorised prior to analysis. An event-related design was used in this study because participants completed tasks taking an indeterminate length of time, rather than simply responding to pre-recorded stimuli.

It was originally intended that an existing multimedia resource would be used for the simulation condition. The existing resources considered each contained 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. The 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. However, as discussed in the following section a number of methodological issues that emerged during our planning and pilot testing required us to depart substantially from this original intention.

Methodological issues identified

Because powerful magnets are used in MRI, it is unsafe to use any device that emits electromagnetic radiation in the scanner and consequently special purpose input and display devices using optical rather than electrical signals are required. An MRI compatible mouse has been developed (see Unterrainer et al., 2004) but was not available for this study. Instead, a button-pad with four buttons was used. The limitations of this device meant that pointing and clicking, scrolling and dragging were not possible, and therefore most readily available multimedia resources were unsuitable. As a consequence, multimedia resources used had to be specifically developed for the study. The resources were designed to use three of the buttons on the button-pad. The left and right buttons were programmed to move a highlight forwards and backwards between options on the screen, and the middle button was programmed to activate the highlighted option (see screen images in Figures 2, 3 and 4). This gave users the ability to interact with the program (e.g. manipulate variables in a simulation) using a relatively simple input device and interface

Physical interaction with a computer requires cognitive processing associated with motor control of the hands and arms, as well as demands on working memory. Consequently, comparing the brain activations while using, for example, a step by step tutorial environment, with activations while using an open-ended simulation or game-based environment, is problematic because of the different levels of physical interaction involved. To eliminate physical interaction as a potentially confounding variable, the simulation resource was structured so that participants would plan their manipulations on one screen, carry out their manipulations on another, and view the simulation output on a third screen. This allows the brain activation while using the planning and output screens within the simulation to be compared with the activation while using the tutorial.

Similarly, the processing of visual information requires cognitive processing in both visual and non-visual areas of the brain. Consequently, comparing users' activation while using a graphical resource with activation while using a text-based resource is problematic. To address this the main parts of the tutorial and simulation resources were designed to have identical screen layouts, with the tutorial resource consisting of a series of output screens from the simulation, but without the ability to control the simulation parameters. In this way the two conditions differed only in the type of interactivity involved in their use.

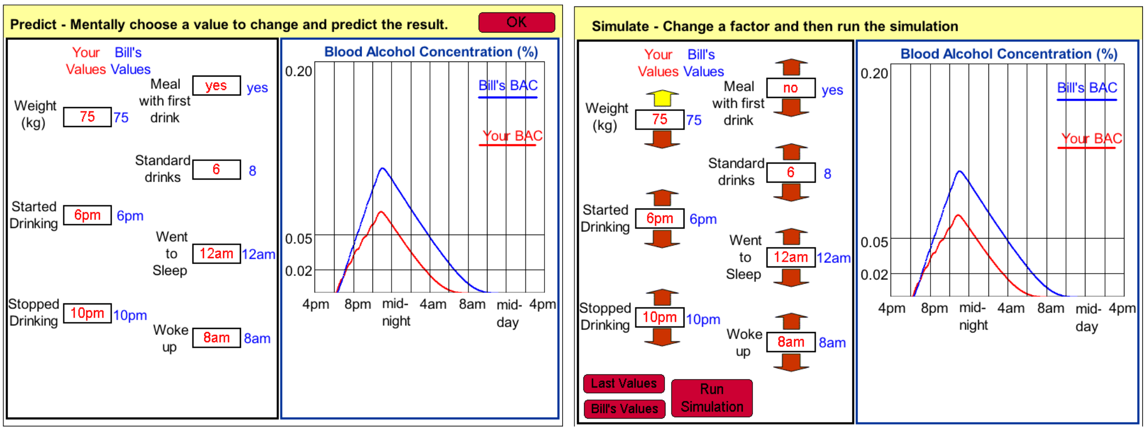
FMRI measures brain activation indirectly by measuring signals that correlate with blood flow. Because blood flow varies from person to person it is not possible to directly compare activations between individuals. Instead comparisons must be made 'within' participants rather than 'between' participants in the first instance. The most important consequence of this is that if cognition occurring through the use of two types of multimedia is to be compared, each participant must use both types of multimedia. This then means that the content and conceptual material contained within each of the resources must differ. If the content were the same participants could apply what they learned in the first resource to their interaction with the second resource. Thus, two different topics were needed to ensure that the material in each resource was ‘new’ to the participant. The need for two different topics leads to potential problems with being able to ensure that the complexity of the material is equivalent across the two resources.

To address this, simulation-based and tutorial-based multimedia resources encompassing two learning domains (blood alcohol concentration and global warming) were developed. This allowed each participant to use a tutorial resource from one learning domain and a simulation resource from the other, and thus allowed analysis to be carried out initially within participant. A counter-balanced design across the eight participants in the study was used, to control for condition order effects (ie, half of the participants were presented with the simulation then the tutorial, and the other half vice versa) and content area order effects (ie, half the participants were presented with the blood alcohol topic followed by the global warming topic, and the other half vice versa).

An additional problem is that an individual’s cerebral blood flow varies slowly over time, due, for example, to mood changes. The customary way to address this is to include regular baseline or rest stimulus conditions to provide a benchmark against which to compare activation. This is problematic for studies such as the one described here that involve holistic tasks, because it means that the participant has to be interrupted from their task in order for the rest stimulus to be shown.

A regular baseline or rest stimulus condition was included within the tutorial and the simulation resource, consisting of random numbers and graphs and an animated highlight. The screen was designed to elicit similar visual processing demands to the main tutorial and simulation output screens. In the tutorial resource, participants viewed a series of simulation output screens with the rest screen displayed between each. In the simulation resource, participants undertook a repeated sequence of planning for a simulation parameter change, manipulation to make this change, viewing of the simulation output as a result of this change and viewing of a rest screen.

The interviews with participants revealed that most participants were able to shift from thinking about the task to 'resting their minds' on the rest screens, although this varied somewhat from participant to participant. The difficulty of producing a true 'rest' state in participants is problematic in all fMRI studies, not only those using holistic tasks. In fact, some researchers have questioned whether a true 'rest' cognitive state is possible in any circumstances (e.g. Stark & Squire, 2001).



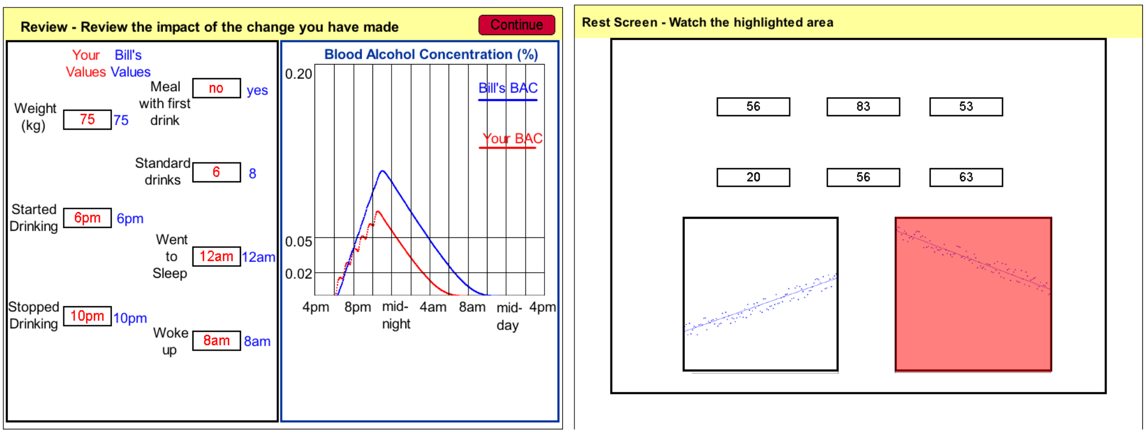
Predict - Mentally choose a value to change and predict the result.

	Your Values	Bill's Values
Weight (kg)	75	75
Meal with first drink	yes	yes
Standard drinks	6	8
Started Drinking	6pm	6pm
Went to Sleep	12am	12am
Stopped Drinking	10pm	10pm
Woke up	8am	8am

Simulate - Change a factor and then run the simulation

	Your Values	Bill's Values
Weight (kg)	75	75
Meal with first drink	no	yes
Standard drinks	6	8
Started Drinking	6pm	6pm
Went to Sleep	12am	12am
Stopped Drinking	10pm	10pm
Woke up	8am	8am

Figure 2.
Example planning screen (left) and manipulation screen (right) from the blood alcohol simulation resource.



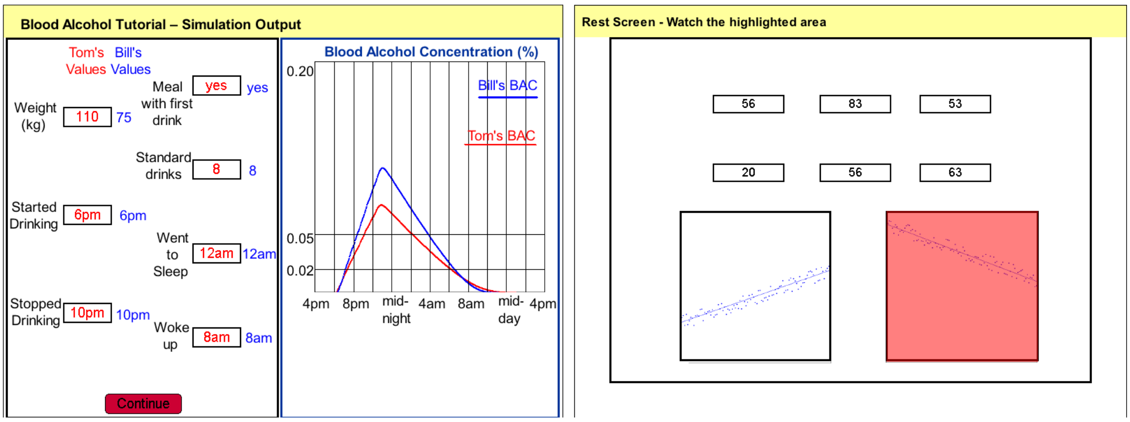
Review - Review the impact of the change you have made

	Your Values	Bill's Values
Weight (kg)	75	75
Meal with first drink	no	yes
Standard drinks	6	8
Started Drinking	6pm	6pm
Went to Sleep	12am	12am
Stopped Drinking	10pm	10pm
Woke up	8am	8am

Rest Screen - Watch the highlighted area

56	83	53
20	56	63

Figure 3.
Example simulation output screen (left) and rest screen (right) from the blood alcohol simulation resource.



Blood Alcohol Tutorial – Simulation Output

Tom's Values / Bill's Values

Weight (kg): 110 / 75

Meal with first drink: yes / yes

Standard drinks: 8 / 8

Started Drinking: 6pm / 6pm

Went to Sleep: 12am / 12am

Stopped Drinking: 10pm / 10pm

Woke up: 8am / 8am

Rest Screen - Watch the highlighted area

Figure 4.
Example simulation output screen (left) and rest screen (right) from the blood alcohol tutorial resource.

Discussion

The methodological issues described above place important restrictions on the interactions possible and the types of task that can be carried out as part of a functional brain imaging study and have important implications for the external validity of the results, or the applicability of the results to more naturalistic settings. It is well accepted that controlling variables in order to maintain internal validity can have a negative effect on external validity in experimental studies in education. This issue has been discussed by a number of authors (see for example Rieber, 2005), however the restrictions discussed here are much greater than those normally encountered.

Probably the greatest potential limitation of the study described above is the imposition of a structure that prevents free exploration and manipulation of the simulation environment. This structure makes the resource quite different to ‘good’ examples of interactive multimedia, and thus will limit the wider application of the results. This said, the similarities between the tutorial and simulation condition will ensure that any differences in activation that are found can be attributed to the key difference between the two resources, that is, the ability to change the simulation parameters.

The requirement that participants undertake their planning and conceptual thinking at certain times and then carry out their physical interactions at other times required a great deal of thought about the design of the resource. In this particular case, a design was able to be conceptualised that allowed the key research questions to be addressed. This may not always be the case for other research exploring cognitive issues associated with interactive multimedia. For example, research exploring cognition associated with the open exploration of a 3D environment such as a computer game would be difficult to carry out using the methods described here.

Additionally, interviews with participants after the pilot study suggest that the degree to which a learner is able to undertake the meta-cognitive self-monitoring required to structure their cognitive tasks so that certain types of thinking are undertaken on certain types of screen varies from participant to participant. It may be that some participants are unable to control their thinking in this way, which will limit the quality of the findings.

It is useful to note, however, that recent functional imaging studies have used more holistic tasks and have carried out a more exploratory type of analysis. The most noteworthy example is the study by Hasson and colleagues (2004) in which participants watched the Clint Eastwood movie, *The Good, The Bad and The Ugly,* while having their brain activations recorded using fMRI. Analyses involved correlation techniques to identify moments where activations were common to all or most participants. The activations at these moments were then explored and, by drawing on the literature, the actual cognition occurring at these moments was able to be postulated. Once techniques such as this have become well established there may be scope for similar analysis techniques to be used with interactive multimedia and, consequently, it may be possible for more holistic tasks without regular baseline conditions to be used.

An additional problem with the use of functional imaging in interactive multimedia research, aside from the methodological constraints described above, is that the results of such studies will not, by themselves, contribute to an understanding of the learning process. Their value depends on the ability of the researcher to interpret the results in light of published results associating brain areas with specific cognitive function in order to make conclusions about the cognitive processing occurring. The potential problem researchers may encounter, however, arises because the types of cognitive task of interest in interactive multimedia research are generally higher order tasks, such as problem solving and synthesising information from a range of sources into a coherent conceptual representation. These cognitive tasks involve activation of a range of areas in the brain and, consequently, it has been very difficult to identify the specific functional purpose of the areas involved. Uttal (2004), for example, has questioned whether localised brain activation patterns can in fact be identified for higher-order cognitive functions. Nevertheless, it is reasonable to expect that the results obtained from studies such as the one described in this paper will be sufficient to allow comparisons with theoretical explanations of prior empirical results. Byrnes (2001) puts this very well:

> *There are quite a number of ways to decompose psychological functions into their constituents. In addition, there are quite a number of ways to explain development. To decide among these possibilities, psychologists need to conduct experiments to 'rule in' certain models and to 'rule out' others. The data from traditional psychological experiments should be combined with data from neuroscientific studies to bolster the claims of a particular theoretical account.*
> (Byrnes, 2001, p.170)

Conclusion

This article has summarised research to date on interactivity and cognition in multimedia learning and has identified a number of limitations of existing research methods. The potential for the inclusion of functional brain imaging methods to supplement traditional behavioural and self-report measures of cognition has been discussed. Although these methods have great potential, when the methodological issues are explored in detail a number of important constraints emerge. Specific constraints identified in a pilot study carried out by the authors were: limitations on learner-computer interaction because of the need to use MRI compatible input devices; activation from motor tasks potentially confounding the results of comparisons between cognition occurring during interactive and non-interactive resources; visual differences between multimedia conditions potentially confounding the results due to activation associated with the visual processing; and problems with the provision of 'baseline' or 'rest' conditions for comparison purposes during holistic problem-based tasks. These constraints have an impact on the degree to which holistic learning tasks can be used within the experiments. As demonstrated in the pilot study discussed, some of these difficulties can be addressed by using specially designed resources that simplify or separate out some of the interactions.

Despite the constraints the use of functional imaging techniques within this field of research has great potential. It is important, however, that brain imaging studies are carried out in combination with non-imaging studies which investigate the use of the similar but less structured resources and which consequently allow the user greater control over the selection and sequence of interactive tasks undertaken. In this way, the external validity of the highly controlled imaging studies can be tested. Furthermore, the new methodological approaches emerging within the cognitive neuroscience community, as exemplified by Hasson et al. (2004), have great potential within this field. These approaches, incorporating analysis techniques that do not restrict the design to conventional block or event-related designs, may allow open-ended, holistic multimedia learning tasks to be experimentally employed, complementing the results of traditional functional imaging studies in this field.

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