Designing Science Simulations in Accordance with Research-Based Guidelines: A Case Study Approach

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Abstract
The applicability of evidence-based guidelines in the design of complex science simulations for a popular online astronomy course is considered in the current paper. Science simulations pose a number of challenges as they tend to deal with complex and/or counter intuitive information, require the manipulation of inter-related parameters and thereby often presume a significant level of expertise from the learner. Through a collaborative approach involving a content-expert, several programmers and an educational multimedia specialist the team were able to more effectively co-design and re-design the simulations to minimise the cognitive load placed upon the student and thereby facilitate more efficient learning.

In terms of the layout of specific elements within the simulations the production process considered the optimal utilization of signaling techniques such as arrows and highlighting and also maximised spatial and temporal contiguity between disparate sources of information in order to minimise any split attention effect. In some cases, the presentation of complex and/or novel information necessitated pre-training in the form of a short audio-visual explanation so as to avoid a mismatch between the learner's level of prior knowledge and skills and the demands of the learning task. Consideration was also given to exemplifying the use of the simulation interface by way of a worked example in cases where it was deemed that the task was sufficiently complex or ambiguous.
The simulations themselves were embedded within an online adaptive learning environment that was supplemented with self-paced lecture material containing both textual and visual elements.

Keywords: multimedia, simulations, animations, astronomy, cognition, evidence based guidelines.

Introduction

The teaching of science often requires the communication of complex or counter-intuitive concepts that can be troublesome to the student cohort (Meyer and Land 2003). The assimilation of such knowledge structures is often facilitated through the use of visualizations ranging from static images, animations and videos through to multi-parameter simulations. Here, we consider the collaborative design of interactive simulations and their subsequent incorporation into an adaptive e-learning environment within the context of an online astronomy course.

The course we are currently upgrading is a popular fully online course that enrolls more than two thousand students per year over three semesters. It provides an introduction to astronomy and the search for life in the universe at a non-mathematical level. The majority of students who take the course are non-science majors. As part of the upgrade we are building tutorial and assessment activities using the Smart Sparrow Adaptive eLearning Platform™.

The tutorial activities were largely built around scientific simulations. Research based multimedia principles (Mayer 2008) guided the design process of the simulations and also assisted the team to judiciously incorporate static images and/or audio-visual material to further support the simulation-based learning activities.

Multimedia design considerations

The relative merit of using static images or dynamic animations for teaching and learning has been regularly investigated by educational psychologists over the last two decades (Mayer 2009). The research reveals that, counter to common belief, dynamic visualizations are often no better than static images for the purposes of student learning (Höffler and Leutner 2007). This finding has been attributed to the inherent transience of animations (Sweller, Ayres et al. 2011) and researchers have endeavored to determine the conditions under which this effect can be ameliorated. As such a number of evidence-based guidelines have been formulated to guide practitioners in the layout and presentation of multimedia material such as stills, animations, videos and simulations (Mayer and Moreno 2003).

Unlike stills and animations, which typically incorporate minimal or no interactivity, simulations often require the student to manipulate inter-related parameters to achieve the learning objective. With regard to science-based simulations in particular, both the inherent complexity of the information and the associated interactivity add considerably to the cognitive load placed upon the student's processing abilities. Consequently load-reducing strategies incorporated into the design and embedding of simulations are critical in working to ensure that the student's cognitive resources are not overwhelmed.

In order to design multimedia resources such as complex simulations for optimal student learning it is essential to understand how a number of factors relating to cognition, prior knowledge and user-control can guide the practitioner in determining the layout and presentation of the subject material.

Human Cognitive Architecture

The assimilation and processing of information through audio visual channels has been shown to be limited by working memory both in terms of capacity and duration. Without mental rehearsal working memory can only hold around seven items (such as digits, letters etc.) for mere seconds (Miller 1956) As such meaningful learning, through the encoding of information into long term memory, can only occur if working memory has sufficient time to rehearse the necessary knowledge structures. The processing of information through this “bottleneck” created by working memory limitations can be better facilitated through the optimization of design considerations affecting the layout, such as the presence of signaling cues and the minimization of any split attention effect incurred by a lack of spatial and temporal contiguity (Kalyuga, Chandler et al. 1999, Mayer 2005). The content expert and multimedia designer can also collaborate to ensure that sufficient levels of prior knowledge have been attained by the learner through pre-training activities (Mayer 2005b)and thus ensure there is no significant mismatch between the students processing abilities and the cognitive load imposed by the learning activity. Prior knowledge structures already encoded into long term memory, referred to as “schemas”, provide a framework that enables working memory to more easily identify and assimilate incoming information.

In particularly complex simulations the student may further be assisted by the presenter “test driving” the simulation to demonstrate a typical scenario in terms of manipulating parameters to achieve a desired learning goal. This is akin to providing a worked example (Sweller 2006) and has been shown to be valuable in terms of modelling to the learner a particular strategy so as to engage with the interface in an effective manner (Hatsidimitris and Kalyuga 2013).

All the above design strategies work together to lower the cognitive load placed on working memory and thereby allow for an optimal learning experience.

Designing the simulations

The simulations are initially designed collaboratively between the content expert and the HTML5 programmer. The draft is then sent to the educational multimedia specialist who considers how research based principles may be incorporated into the design and subsequently makes a number of recommendations to the content expert and programmer. If the proposed amendments to the design “make sense” and do not require inordinate amounts of time to implement then a revised simulation will be created.

The guidelines most often considered were those that minimise the split attention effect i.e. spatial/ temporal contiguity principles and also the signaling principle, which basically informs the learner where they should direct their visual attention at any given point in time. Signaling is particularly important in complex visualisations as research has shown that novices tend to focus their attention on what appears “perceptually salient” rather than that which is “thematically relevant” (Lowe 2008).

In Fig.1 the interactive multimedia requires the learner to sequentially drag the small thumbnail pictures to the correct location along the timeline. As the timeline covers many millions of years there is a slider to allow the learner to scroll across the entire historical timeline of the universe since the "big bang". In the initial draft the slider was not indicated by a semi-transparent red layer and so this visual cue was added as a signal to indicate a key point of interactivity. Further to this, in the initial draft a correct solution only entailed a textual response of "correct" but it was later decided that it could also be accompanied by a short textual summary of what the time-event entailed. Presenting this factual material within this context provided for temporal contiguity as the learner didn't need to recall knowledge that may have only been acquired beforehand from the online lessons.

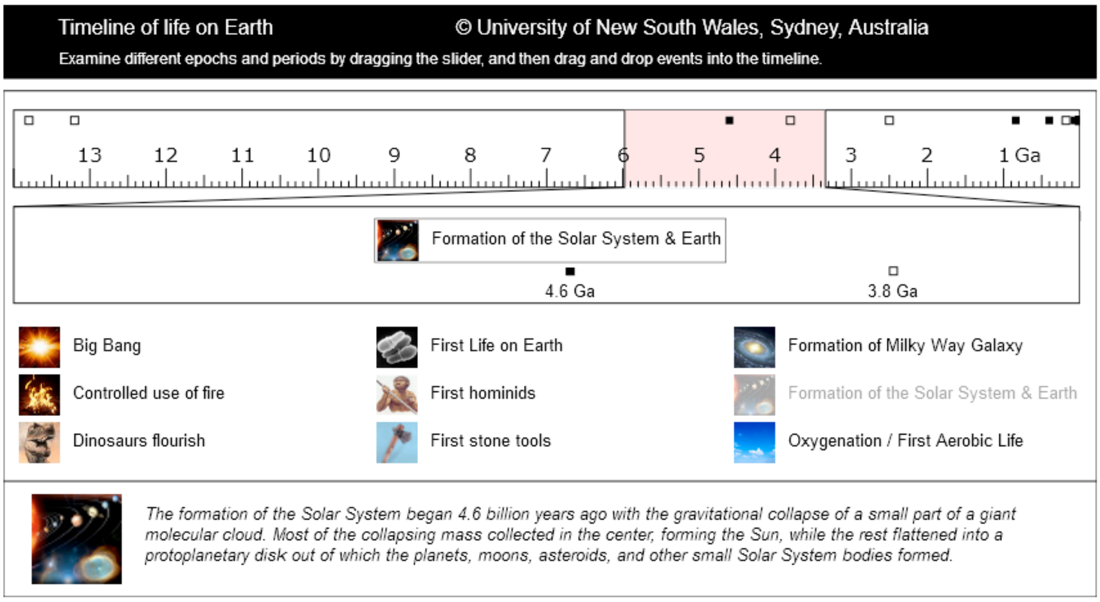

Fig. 1 Interactive "Timeline of Life on Earth" activity had multimedia principles applied in a simple but effective manner.

Embedding simulations within the broader learning context

The multimedia designer can consider the applicability of design principles that reflect the general limitations of human cognitive architecture. This is referred to as reducing extraneous cognitive load (Sweller 2010). However, in any given learning activity it is the content expert can avail themselves of multimedia guidelines that serve to minimize any mismatch between the difficulty and complexity of the material and the current state of the student's skills and prior knowledge. This strategy is referred to as reducing intrinsic cognitive load (Ayres 2006) as it is particularly concerned with the level of difficulty inherent in knowledge structures as perceived by the student, given their level of prior knowledge. In this case the teacher can best gauge the need for incorporation of principles such as segmentation and pre-training to enable the student to more effectively learn new or complex information.

The segmentation principle operates on the basis that intervals between small segments of information will allow the user more opportunity to process the information than one continuous stream of information (Ali and Madar 2010). This principle is evident in the interactive tutorials in so far as they are composed of a series of self–paced "slides". Segmentation is usually most beneficial when information is in the form of a particularly extended text, video or animation. However, in the case of simulations per se the user initiates and controls changes in the state of the visuals through the self-paced manipulation of parameters and as such the segmentation principle need not be applied. Nevertheless the complexity inherent in the inter-related manipulation of several parameters lends itself to a multitude of combinations and so pre-training can provide crucial information to guide the learner's strategic use of the interface.

The pre-training principle basically states that the learner would use their time more efficiently when encountering complex information such as found in animations, videos and simulations if they were first instructed to identify and understand the key elements. In conjunction with this principle is the guideline advocating worked examples as a means of modelling or demonstrating to the student a particular strategy to adopt in solving on or more problem states (Sweller 2006). Research by Hatsidimitris and Kalyuga (2013) further demonstrated that providing a worked example to students regarding the efficient use of an interface in a recall task resulted in significant increases in the overall student performance. Keeping these principles in mind the project team are working towards providing a level of pre-training that not only sequentially introduces various elements of the simulation but that also seeks to exemplify a strategic use of the interface in order to achieve a required inter-relationship of parameter settings. This two-fold approach i.e. introducing the various onscreen elements and then demonstrating the simultaneous manipulation of parameters to achieve a learning goal is particularly relevant to the more complex scenarios evident in some of the simulations.

Conclusion

The collaborative design and production of educational simulations requires team members with expertise with respect to the subject matter, design principles and the logistics and costs of graphics-based software and programming languages. At the "micro" level one needs to evaluate the simulation in terms of its layout and implement revisions, particularly in terms of signaling and spatial contiguity, so as to lower the cognitive "hurdle" imposed by the learning task. At the "meso" level one must ensure that particularly complex simulations are accompanied with pre-training that introduces the various elements and, where deemed necessary, a demonstration of how to manipulate the parameters to achieve a "critical" state or inter-relationship. At the "macro" level the simulations, if provided as an assessment task, need to be supported by corresponding background information in the lesson material and should reflect the overall key learning objectives of the course. In an ideal world, given the cost and resources involved in generating simulations, the teaching resources should be both downloadable and re-usable in different learning environments.

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