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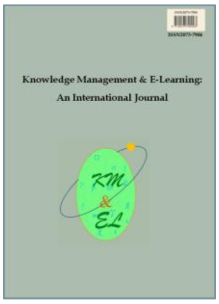

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A theory-to-practice approach for teaching science with animations

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A theory-to-practice approach for teaching science with animations

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Abstract: Educational psychologists have for decades conducted research into the most efficient manner by which information can be assimilated through dynamic visualizations such as animations and video. As a result, a number of research-based guidelines have been formulated to guide the designer, teacher and learner regarding the layout, presentation and self-regulation of transient information. How to apply multimedia learning principles in a considered and creative manner when teaching or learning with dynamic information in a regular classroom situation? This article presents a practical and visual guide for dealing with some of the key issues, such as split attention, signaling, segmentation and strategic learner-control. Some classroom orientated suggestions are offered for the incorporation of these principles when using animations for teaching complex information. The overall objective is to organize the pacing and sequencing of the dynamic information in a manner that is optimally aligned with the students' prior knowledge and cognitive processing ability.

Keywords: Multimedia; Animations; Video; Guidelines; Cognition

Biographical notes: George Hatsidimitris is an educational multimedia developer at the School of Physics, The University of New South Wales, Australia. He has received an Australian Learning and Teaching Council Citation 2006 for displaying leadership in the development of exciting and engaging learning and teaching spaces and online multimedia resources in physics. His research interests include educational multimedia guidelines and the self-regulation of transient information.

1. Introduction

Based on models of human cognitive architecture, researchers in the field of multimedia learning have formulated a range of evidence-based guidelines to inform the practitioner with regard to the layout and presentation of multimedia teaching materials such animations and videos (Mayer, 2009). Nevertheless, the adoption of such principles into the classroom does not appear to be widespread and this may be due in part to the lack of clear instructional examples as to their applicability to classroom teaching resources. The present paper briefly outlines the problem with audio visual material in terms of its inherently transient nature and then proceeds to illustrate the incorporation of several multimedia principles through simple but effective classroom-based techniques. The initial objective of communicating a simplified model of cognition is to enable the educator to appreciate the critical role that a severely-limited working memory plays in the processing of transient information. The ensuing illustrations exemplify to teachers how they may use cognitive design principles in order to adapt the presentation of videos and animations to levels of classroom expertise so as to ensure there is no significant mismatch between the teaching materials and the students ability to assimilate the information.

2. Human cognitive architecture

The relevance of Human Cognitive Architecture for assisting the instructional designer in determining the layout and presentation of multimedia learning materials is considerable. Efficiencies in learning can only be optimized when the organization of the learning material is attuned to the configuration and limitations of human information processing structures. The central and decisive element of this cognitive architecture has long been recognized as working memory (WM). Sweller, van Merrienboer, and Paas (1998) state that working memory can be equated with consciousness. In previous times, the processing capabilities of WM had not been established and the mistaken presumption that this aspect of our cognitive architecture was primarily responsible for temporary storage had led to it being misleadingly termed short term memory (Baddeley, 1992). In fact, the role of WM is to actively process the incoming information, usually through a procedure involving integration and rehearsal, so that it may eventually be encoded into long term memory.

Miller (1956) established through controlled experimentation that WM is severely restricted in its capacity to store more than several novel elements for any longer than mere seconds. As such it acts as a bottleneck between the streams of information that can enter through our sensory modalities and the seemingly limitless banks of knowledge that comprise long term memory. Developing effective instructional strategies to either circumvent WM limitations or to ensure that available WM resources are utilized in an optimally efficient manner is the core pursuit of educational psychologists in the field of multimedia learning. Despite the limitations of cognitive-based theories of learning in their abilities to fully account for socio-cultural, motivational and affective components related to the learner’s ability to build new knowledge structures, it is nevertheless desirable that all instructional design professionals should be mindful of WM limitations. Learning by animations, particularly whereby novel and complex knowledge needs to be assimilated at a pre-determined speed, is the type of high cognitive load task that requires particularly strategic alignment between design elements incorporated into the learning materials and the learner’s bounded ability to process this information as determined by human cognitive architecture.

Information presented during a learning task is initially assimilated for processing through the senses and in the particular case of animations, through visual and auditory channels (see Fig. 1). At the sensory level, information is selectively assimilated to undergo further processing in WM that may entail integration, rehearsal and ultimately encoding. The resultant transformation of this new knowledge into cognitive constructs known as schemas in long term memory (LTM) is the process whereby meaningful learning takes place (Sweller, 1999). LTM is comprised of a seemingly endless bank of knowledge in the form of inter-related schemas. Unlike WM there is not a capacity of duration limitation associated with LTM (Sweller, van Merrienboer, & Paas, 1998).

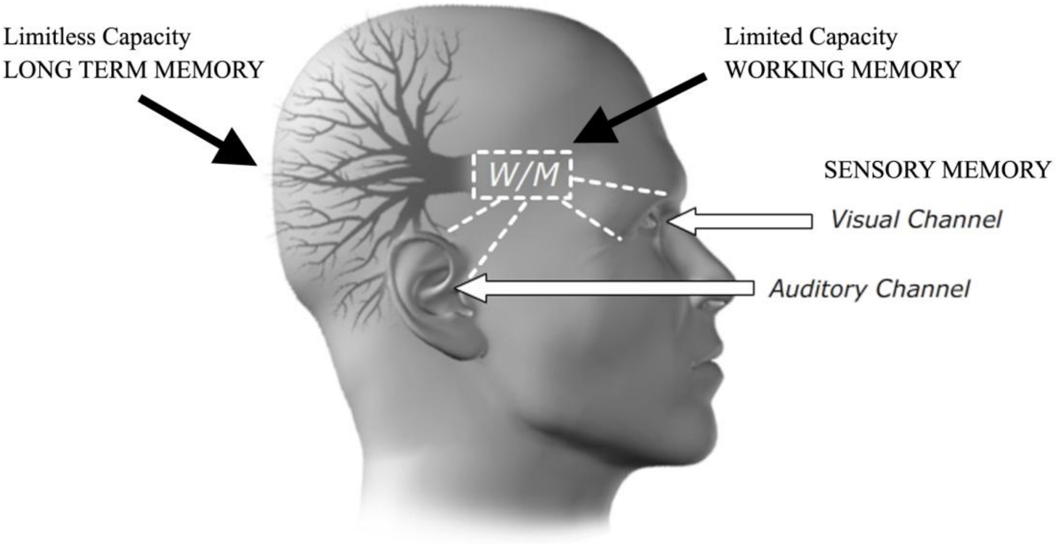
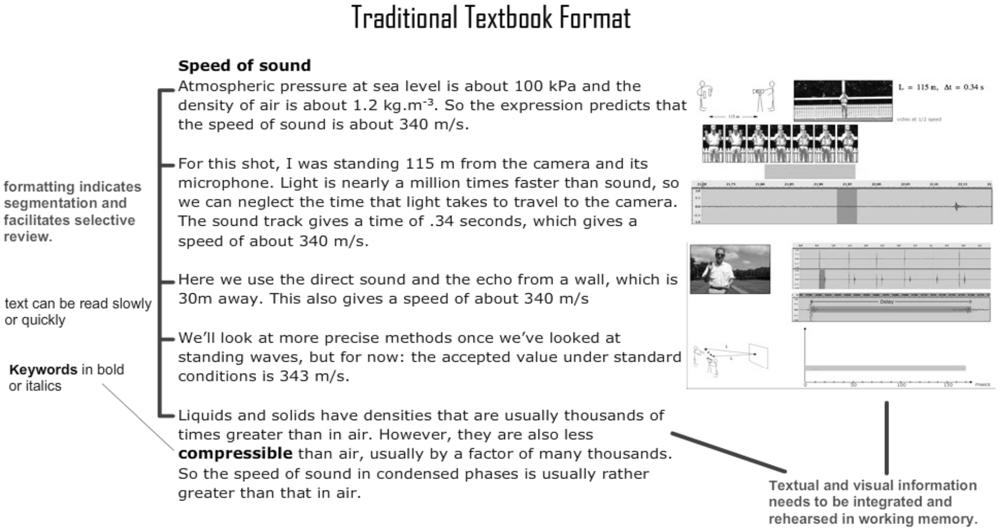


Fig. 1. A symbolic representation of the key components of human cognitive architecture

In working memory theories, such as proposed by Baddeley (1992), it is commonly postulated that a separate Central Executive structure acts to oversee the organization and processing of incoming information. The current thesis utilizes a theoretical framework which argues the existence of a Central Executive is more logically understood in terms of LTM schemas that fulfill the same role (Sweller, Ayres, & Kalyuga, 2011). The inter-relationship of LTM to WM is such that relevant long term schemas can be retrieved so as to facilitate, or expedite, the transfer of associated incoming information through WM to LTM, thereby freeing up WM resources to deal with further incoming information. If, for example, a learner has a pre-existing schema that allows her/him to identify the keys on a piano that correspond to the notes on a musical staff, then this learner will find it easier to master a basic piano piece than a novice with no such knowledge structure in his/her bank of prior knowledge. Although WM is limited to several novel elements of information at any given time, the classification of what constitutes a discrete element is dependent on the learner’s pre-existing schemas. Learners who have already mastered the alphabet can progress from seeing each distinct letter as a novel element to perceiving new words, or “chunks” of letters, as imposing a load comparable to that previously placed on WM by one letter. Chunking of elements or relating novel information to pre-existing schemas, albeit schemas that contain general domain knowledge, are mechanisms by which prior knowledge can ameliorate the cognitive load placed on WM during a learning task.

3. The problem with animations and film clips

Traditionally, learners have often studied new information utilizing paper-based documents that incorporate textual and graphical content (see Fig. 2). In this scenario the learner’s visual access would allow them a “bird’s eye view” of the learning material and certain markers such as paragraphing, headings, italics etc. could be utilized to navigate the material. As such it was easy to note the underlying structure of the material, selectively re-read paragraphed subdivisions, skip ahead of sections whereby the headings indicated previously learnt information and so forth. In a comparable manner the reader could view and examine the static images repeatedly and for as long as necessary. This seemingly intuitive mode of studying paper based material effectively allows the learner to utilize a flexible study technique incorporating self-paced and self-sequencing strategies so as to fulfill the learning objectives in a manner that aligned with the students level of prior knowledge and cognitive processing abilities.



Traditional Textbook Format

Speed of sound

Atmospheric pressure at sea level is about 100 kPa and the density of air is about 1.2 kg.m^{-3}. So the expression predicts that the speed of sound is about 340 m/s.

For this shot, I was standing 115 m from the camera and its microphone. Light is nearly a million times faster than sound, so we can neglect the time that light takes to travel to the camera. The sound track gives a time of .34 seconds, which gives a speed of about 340 m/s.

Here we use the direct sound and the echo from a wall, which is 30m away. This also gives a speed of about 340 m/s

We'll look at more precise methods once we've looked at standing waves, but for now: the accepted value under standard conditions is 343 m/s.

Liquids and solids have densities that are usually thousands of times greater than in air. However, they are also less **compressible** than air, usually by a factor of many thousands. So the speed of sound in condensed phases is usually rather greater than that in air.

formatting indicates segmentation and facilitates selective review.

text can be read slowly or quickly

Keywords in bold or italics

Textual and visual information needs to be integrated and rehearsed in working memory.

Fig. 2. Example of text-plus-pictures format, as is often used in textbooks

The advent of education technology has brought with it a qualitatively different approach to presenting learning material and by default necessitates a distinctively altered path to assimilating information. In the case of instructional animations, at any given point in time the learner can only see one small snippet of information, much like moving a magnifying glass over a page of otherwise inaccessible information. All the "landscape" signaling previously available in the textbook format has suddenly disappeared and in its place we typically find a more periscopic view of the learning material. Time constraints and associated transience of information add to the challenge of learning with animations. In audio-visual presentations the difficulty is further compounded as both verbal and visual channels must maintain effective processing rates for potentially complex and novel information.

In audio-visual presentations, what was traditionally represented in printed text often becomes a narration or voice-over. In this audio modality, the learner is typically no longer able to view the structure of the material nor adjust the speed of the narration other than to pause and resume. Further, multimedia presenters and producers take advantage of their media to replace static representations (photos or sketches) to dynamic visualizations (film clips or animations). The latter show more features of real-world phenomena and in particular show the time dependence of phenomena and quantities. However, they are more likely to overwhelm the learner's limited cognitive resources (Tversky, Morrison, & Betrancourt, 2002). Together, audio-visual representations of complex material introduce both auditory and visual transience into presentations, and both of these have a tendency to overload the student's limited working memory capacity and thus impede meaningful learning. The likelihood of this happening rises as the difficulty of the material increases or when encountering students with lower levels or prior knowledge.

The creation of animations and film clips tend to be more expensive than producing static images and research has shown that stills tend to be as good or better than their dynamic counterparts about 50% of the time (Höffler & Leutner, 2007). Nevertheless, there is a general consensus that some forms of information, particularly scientific phenomena involving motion or complex mechanical systems, are particularly amenable to illustration through dynamic visualizations as evidenced by a proliferation of educational animations and film clips on the internet. As such the adoption of evidence-based guidelines into the multimedia classroom is of particular interest to teachers hoping to introduce complex scientific information in a manner that is cognizant of the fact that students must assimilate information at a rate that is in line with limited cognitive processing abilities and low levels of prior knowledge (Sweller, Ayres, & Kalyuga, 2011). The manner in which this can be achieved might best be understood in terms of research-based principles relating to both the layout and format of the information and those guidelines that are concerned with the presentation of the multimedia information so that it accords with the students level of prior knowledge (see Fig. 3).

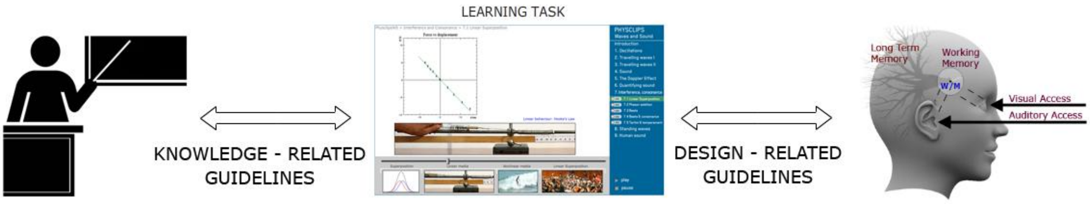


Fig. 3. Multimedia learning principles generally fall into two groups: those that analyze the presentation of the material as a function of the student's level of prior knowledge and those that concern the design of the layout.

4. Design-related guidelines

Multimedia information is generally assimilated through the dual channels of hearing and vision. These two modalities are sometimes referred to as the phonological loop and the visuospatial sketchpad (Baddeley, 1992). If the information is novel and/or complex, it usually needs to be integrated and rehearsed in working memory before it can be encoded into long-term memory whereby meaningful learning takes place. The designer can reduce the mental load placed upon working memory through the application of particular guidelines relating to the layout and the subsequent assimilation of information through the engagement of the dual modalities. Often however the dynamic information has been designed and engineered on a purely intuitive basis with little or no regard to evidence-based guidelines. Consequently the information is not optimally aligned with the structure and limitations of the student's human cognitive architecture, resulting in inefficient learning and the likelihood of cognitive overload.

Sometimes, however, the teacher may be able to identify shortcomings in the design and subsequently adapt the presentation of the material to ensure more effective student learning. In other cases, whereby the resources may have been designed for more advanced learners, the presentation of the material can be re-sequenced in a manner that allows the student appropriate amounts of time to integrate and process the requisite information. The majority of the techniques outlined here, and in the next section, are largely based on the notion that learners could move from stills to animations as their level of expertise increases (Hatsidimitris & Wolfe, 2010; Kalyuga, 2008). Thus the teacher might, for instance, be able to improve student learning performance by either pausing the animation at identified points of complexity, or beginning with a static screen grab, in order to provide some preliminary knowledge structures and accompanying instructional advice regarding the viewing and assimilation of the information. In so doing, the teacher will ameliorate some of the negative effects often encountered when novices attempt to learn complex information presented in a transient format.

4.1. Signaling

Signaling (Mayer, 2005) refers to highlighting the critical aspects of the visual material to which the student should focus their attention. This may take the form of overlaid arrows, labels, fading and so on. Often invisible forces can be indicated through the use of overlays (see Fig. 4 below).

Research has shown that students, particularly novices, often focus on perceptually salient aspects of complex visual information and miss the thematically relevant components (Lowe, 2008). The teacher need not hesitate to stop an animation/film clip and point to the critically important aspects of the material that should form the focus of the student’s attention, particularly if effective signaling techniques have not been incorporated into the animation or film clip. As with many of the guidelines, most teachers utilize them intuitively when teaching from the whiteboard but may overlook the need to intervene in the showing of an animation or film clip where the likelihood of cognitive overload is even higher.

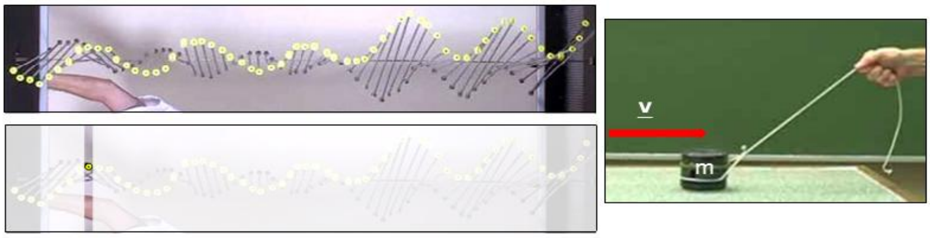


Fig. 4. At left, fading of most of the image is used to isolate one component of the wave machine in order to show that any one particle in the medium conducts its own oscillation (here simple harmonic motion) and that it is the collection of these oscillations that produce standing or travelling waves. In the photo at right, simply placing an arrow above a mass indicates the direction of its velocity and therein provides a point of focus for the student’s attention.

4.2. Spatial and temporal contiguity

Spatial contiguity can minimize split-attention effects through the co-location of otherwise disparate sources of information, thus avoiding the scenario wherein the student is looking back and forth between two elements that need to be integrated (see

Fig. 5). If students need to integrate multiple sources of information then these elements should be spatially contiguous so as to minimize the level of mental effort required (Mayer, 2005).

Fig. 5. One traditional format is providing a legend (shown on the right). This creates a source of split attention for the student. Superimposing the labels on the graphic, as at left, can lower the degree of mental effort required to integrate the information.

Teachers have a number of options to deal with split-attention effects arising from temporally or spatially disparate sources of information. If the teacher identifies a lack of spatial contiguity then they could pause the animation to allow suitable time for the students to integrate the information. Alternatively, the teacher could provide a handout/worksheet prior to the video wherein the elements have been reworked in a spatially contiguous manner. If information is presented at a later period in the animation that would have been better represented simultaneously then the teacher may take a number of screen grabs and then present the material side by side in a manner exemplified in Fig. 6.

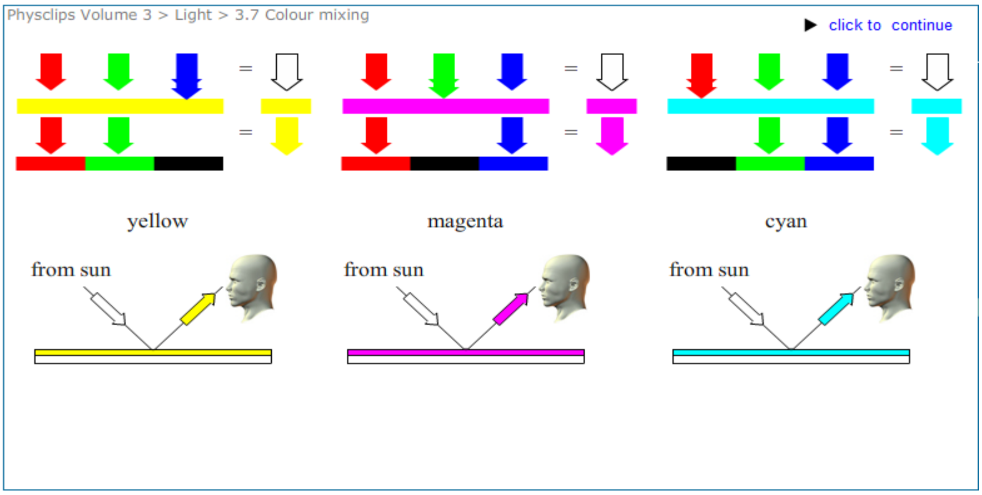


Fig. 6. The subtractive mixing of different colors (here the subtractive primaries) was displayed and explained sequentially in this multimedia tutorial starting with yellow and then moving to magenta and cyan. The summation of the processes remained on screen whilst the animation was paused (thus enabling temporal contiguity) such that the learner

might compare, contrast and thus integrate the information at their own pace (note the "click to continue button" added to this design to force a pause and yet allow the learner to resume the animated tutorial once the information has been assimilated).

4.3. *Modality principle*

One strongly-recommended inclusion in audio-visual material is a voiceover (Mayer, 2008). In traditional textbook, studies the learner reads the text and views the images via the visual channel and this process must be undertaken repeatedly in order to integrate the textual material and the imagery. However with audio-visual material the narration and the animations engage both visual and auditory channels, allowing the presenter an opportunity to integrate the information. The strength of the modality principle relies on the synchronicity between what is being spoken and what is being shown in the animation. Talking about the animation and then showing it, for example, would entail a loss of temporal contiguity and lead to less efficient learning outcomes (Mayer, 2005).

In classroom use, the teacher can mute the narration of an animation and provide their own explanation that might be more in line with the student's particular level of expertise. In this scenario, the educator should at all times seek to provide specific narration for the section of the animation currently in view and may further utilize signaling devices (perhaps with a pointer or hand gestures) to direct the students attention.

5. Presentation-related guidelines

The design-related guidelines were focused on how the teacher might optimize the student's efficient assimilation of information through the use of signaling, spatial contiguity and the engagement of both modalities. The educator can also increase efficiencies in learning by aligning the difficulty of the presentation so as to accord with the expertise level of the students. This typically requires the teacher to adapt the presentation of the learning material to a format that is less challenging than one continuous stream of information.

5.1. *Segmentation*

Rather than showing an animation in one continuous whole, the effect of segmenting into conceptually discrete re-playable portions can benefit student learning (Spanjers, van Gog, & van Merriënboer, 2010). Segmenting indicates to the student the underlying structure of the presentation, whilst also enabling the learner to pause between segments to process information (see Fig. 7). Students need to rehearse new subject material before learning takes place. Where it is possible, it is useful for them to learn to pause the presentation at conceptually-discrete intervals so as to allow revision and processing of the information.

5.2. *Pre-training*

During a complex animation the learner may be required to assimilate information at two levels. On the one hand the learner would be expected to be familiar with the identification and configuration of visually identifiable elements. On another level the learner would also be required to note the motion that takes place between the elements. If the learner is not familiar with all the characters or components of the mechanical system or concept at hand then it would be difficult to also note the pattern of movement that takes place. To lower the mental load necessary in understanding complex animations, the teacher can begin with a still from a screen grab, perhaps of a particularly complex point in the animation, and introduce all the components that interact during the animation. Following this initial level of pre-training, the learner will then be able to focus his attention on understanding the behavioral or functional aspects of the animation (Mayer, 2005b).

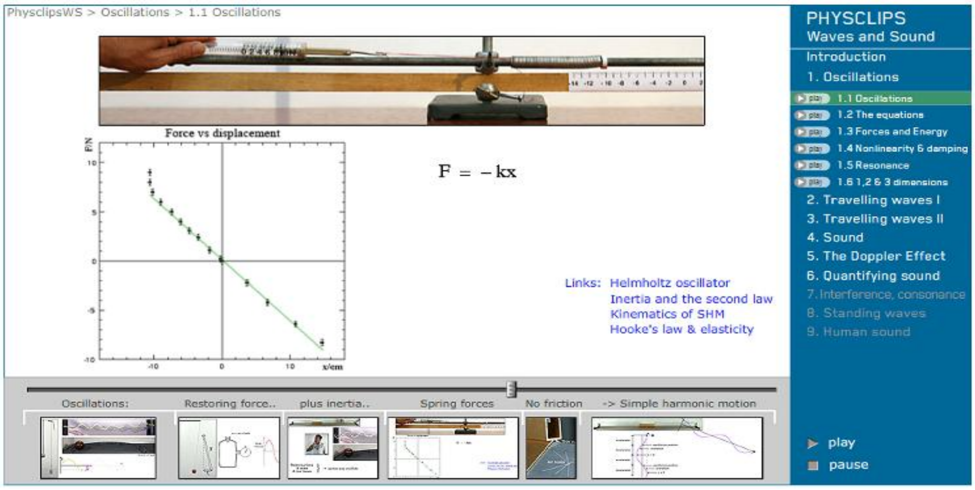


Fig. 7. In the above example, segmentation of the multimedia tutorial is represented by the relevant thumbnail pictures below the scroll-bar. This allows the user to scroll to any particular sub-section for revision.

6. Passing control to the learner

Students are often required to study learning material independently through the use of animations. In this type of learning scenario the student may easily overestimate his/her ability to process transient information in a meaningful manner and could benefit from specific instructional advice. A recent study (Hatsidimitris & Kalyuga, 2013) showed that providing explicit instructional advice on how to self-regulate transient information can improve student performance. In the pilot study, the participants were required to either view free-running narrated science animations a number of times or alternatively to self-regulate the pacing and sequencing of the transient information through a flexible means of learner control (in this case a timeline scrollbar). No significant difference was found between the two groups. In the follow up experiment the participants who were provided with learner control were explicitly shown how to manage the complex stream of transient information i.e. by revising conceptually-discrete segments so as to overcome auditory transience and, in conjunction or alternatively, pausing (or scrolling slowly across) the presentation so as to integrate spatially/temporally disparate sources of visual information. Students with low levels of prior knowledge showed significant improvement when explicitly directed to undertake such rehearsal and pacing strategies in a manner that reduced the cognitive load associated with the transient information. The implication of these findings, in that different modes of transient information (i.e. auditory or visual) require different learner control techniques for optimal assimilation, has formed the rationale for much of the teacher-training strategies discussed throughout the current paper.

Demonstrating the classroom techniques outlined throughout the current paper may also assist in communicating to the student the need to actively pause, revise and integrate transient information in a manner befitting the complexity and novelty of the subject matter. Schnotz and Lowe (2008) suggest that highly complex animations might be reviewed a number of times with each iteration noting different aspects of the motion being studied. This procedure could be conceptualized as a combination of rehearsal, segmentation and signaling in so far as the subject matter is repeated whilst the educator signals a different segment of the material to which the student should focus their attention.

7. Conclusion

Although animations appear to be intuitively superior to static images, research-based investigations suggest that dynamic visualizations are prone to overwhelming the student's limited information processing ability. To overcome the negative effects associated with transient information the teacher can actively adopt a number of techniques that may include pausing the presentation, replaying complex segments, signaling thematically relevant elements and narrating the animations in a synchronous and descriptive manner that is attuned to the student's level of prior knowledge. Further, the learner could benefit from being instructed as to the manner of self-regulation of animated material in terms of pausing to integrate visually inter-related elements of information and reviewing conceptually discrete segments of audiovisual material so as to facilitate encoding into long-term memory. The motivation and rationale for the current paper emanates partly from the wealth of research concerning the applicability of research-based guidelines for the design of educational multimedia (Mayer, 2009) and partly on recent research that suggests learners require instructional advice to optimally assimilate complex information through the use of dynamic visualizations (Hatsidimitris & Kalyuga, 2013). The extent to which these findings are transferable to a teaching situation, although seemingly self-evident, requires quantification and remains a goal of future research for the author. Multimedia presentations exemplifying some of the classroom techniques discussed in the current paper are being produced by the author and can be viewed at http://www.animations.physics.unsw.edu.au/teaching-resources/.

Acknowledgements

Examples of physics animations were excerpted from the Physclips project with the kind permission of Joe Wolfe, *see* http://www.animations.physics.unsw.edu.au/.

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