Applying the cognitive theory of multimedia learning: an analysis of medical animations

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CONTEXT Instructional animations play a prominent role in medical education, but the degree to which these teaching tools follow empirically established learning principles, such as those outlined in the cognitive theory of multimedia learning (CTML), is unknown. These principles provide guidelines for designing animations in a way that promotes optimal cognitive processing and facilitates learning, but the application of these learning principles in current animations has not yet been investigated. A large-scale review of existing educational tools in the context of this theoretical framework is necessary to examine if and how instructional medical animations adhere to these principles and where improvements can be made.

METHODS We conducted a comprehensive review of instructional animations in the health sciences domain and examined whether these animations met the three main goals of CTML: managing essential processing; minimising extraneous processing, and facilitating generative processing. We also identified areas for pedagogical improvement. Through Google keyword searches, we identified 4455 medical animations for review. After the application of exclusion criteria, 860 animations from 20 developers were retained. We randomly sampled and reviewed 50% of the identified animations.

RESULTS Many animations did not follow the recommended multimedia learning principles, particularly those that support the management of essential processing. We also noted an excess of extraneous visual and auditory elements and few opportunities for learner interactivity.

CONCLUSIONS Many unrealised opportunities exist for improving the efficacy of animations as learning tools in medical education; instructors can look to effective examples to select or design animations that incorporate the established principles of CTML.

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INTRODUCTION

Medical students must learn a great quantity of physiological and pathophysiological processes, surgical procedures and therapeutic interventions. Increasingly, instructors have turned to technology-assisted materials such as animations to provide students with the most accurate representations of these processes and techniques.[1] Animations, which consist of a series of dynamic, graphical elements that represent real-world phenomena, present a complex concept in an efficient manner by substituting long textual descriptions with images in motion.[2] Compared with static images or textual descriptions, animations 'analyse processes and movements, simplify complexities through the use of symbols, emphasise pertinent information through the use of colour, highlight through changes in speed, stress action with sound'.[3] Therefore, animations create an experience that is both engaging and instructive.

Animations that have positive learning effects may be difficult to construct because of the complex subject matter involved and the technical skills required to create high-quality computer-based animations. For this reason, educators may use existing animations to present educational content. In medical domains, examples of instructional animations include a demonstration of epithelia and their attributes (i.e. shape of cells, location in organs),[4] a dynamic histological process such as bone formation during embryogenesis,[4] three-dimensional animations of cleft lip and palate surgical techniques,[5] and ocular anatomy and technical skills in cataract surgeries.[6] Given the usefulness of animations in conveying complex information and the large body of research indicating that animations that follow certain empirically established design principles facilitate learning of medical and other scientific material, it is our goal to assess the extent to which existing animations adhere to these principles and how instructors can select and develop effective animations.[2,7,8]

Instructional design principles in animation development

The main design guidelines for animations are grounded in the cognitive theory of multimedia learning (CTML).[8] To the authors' knowledge, there are no other comprehensive theories of multimedia design. Despite the rapid changes in the instructional technology adopted in medical education, CTML is a useful framework because it has extensive empirical support and builds on other established theories, such as dual coding theory[9] and cognitive load theory,[10] to help explain and predict a variety of learning outcomes. According to dual coding theory, images and words are processed in separate, limited-capacity channels of working memory before becoming integrated into a single, coherent mental model, which is an organised conceptual framework of the subject matter at hand.[8,9] Verbal and pictorial components provide unique contributions to mental model formation: words contribute theory-based information, such as explanations of complex relations, and images contribute similarity-based information, such as exemplars or other basic visual representations.[11] The generative process of combining these theory-based and similarity-based elements to construct a detailed mental model helps learners solve related problems and anticipate future events in that context.[12,13] Thus, animations that use words and images appropriately are potentially ideal tools for aiding student learning.

Also linked to CTML, cognitive load theory incorporates learners' cognitive capacity for forming mental models into the designing of instructional materials, such as animations.[10,14] An effective animation contains sequences of motion frames and presents the essential attributes of a concept in a manner that facilitates learning.[15] Animations that accomplish this goal are designed with the learner's cognitive capacity in mind and aim to optimise the balance among three types of cognitive demand: essential processing; extraneous processing, and generative processing.[14,16] Each type of processing imposes a different type of load for the learner, and each needs to be addressed in a specific manner to facilitate learning. Essential processing, which imposes intrinsic load, is the cognitive processing inherently required by the nature of the task to mentally represent the lesson content. Extraneous processing, which imposes extraneous load, involves inefficient mental activities in which learners engage when faced with irrelevant or ineffective learning situations (e.g. distracting sound effects and images that are separated from their verbal descriptions). Generative processing, which imposes germane load, occurs when the learner creates a coherent mental model of the subject at hand. This type of processing, although effortful, is necessary for the learner to understand the topic as well as the overall learning domain. The instructional design of animations should attempt to manage essential processing, minimise extraneous processing and facilitate generative processing.[16] In the following paragraphs, we discuss in more detail how this balance can be achieved.

The cognitive theory of multimedia learning provides several evidence-based learning principles that instructors should follow to optimise processing demands and facilitate learning.[8,17] Although there are many principles of CTML, for space considerations we will restrict our discussion to eight principles which are among the most empirically supported and easily implemented in terms of their ability to support the management of essential processing, reduce extraneous processing and facilitate generative processing. Studies supporting CTML have been conducted in classroom, workplace and laboratory environments and have included subjects ranging in age from children to older adults.[18–21] It should be noted that these principles – as well as the purpose of this paper – focus on short multimedia animations, which represent only one type of instructional tool that may be implemented in an entire curriculum. Brief definitions of these eight core principles are summarised in the first two columns of Table 1, and each is discussed in more detail below.

To manage essential processing, the pre-training principle states that key terms should be defined prior to the main lesson content. By providing key terms before the main lesson, learners experience less intrinsic load during the lesson because they are focusing only on lesson content rather than on content plus vocabulary. Thus, learners have an increased ability to efficiently construct schemas and mental models during that time.[19,22]

Another principle for the management of essential processing is the modality principle, which suggests that words should be presented aurally instead of visually to make the most efficient use of both verbal and visual processing channels.[9,23,24] The rationale for this principle rests in dual coding theory: when learning, students can process information in both visual and verbal channels simultaneously. If the learner uses his or her visual channel to process any images or animations, presenting on-screen text to convey verbal information merely divides the learner's visual attention and reduces the efficacy of the lesson.[25] Even though visual verbal information (i.e. on-screen text) is eventually processed in the verbal channel,[9,26] visual channel resources are required to initially identify and 'send' the information to the verbal channel. By presenting verbal information aurally, the learner can eliminate these extra steps and demands on the visual channel, leading to an efficient use of resources, and thereby optimising the learner's cognitive capacity.

There is some debate on the exact cognitive mechanisms responsible for the modality effect, as well as the conditions under which it is observed. For example, a recent meta-analysis of studies investigating the modality effect defined two separate modality effects, of which one is for simple verbal items and one is for multimedia items.[26] Although this debate is theoretically interesting, we feel that an in-depth discussion on working memory processes and models is beyond the scope of this paper. Regardless of the mechanisms at work, the modality effect has been found repeatedly using the type of materials we reviewed (i.e. short, animated scientific explanations) and we believe that, for practical purposes, the empirical outcomes are more important. For example, the modality effect occurs most noticeably with short (i.e. < 10 minutes) and computer-paced lessons; when learners can control the pace of the lesson, intrinsic load may be diminished, lessening the impact of the text's modality on learning outcomes.[26,27]

Principles that can reduce extraneous processing, and thus alleviate extraneous load, are the coherence principle, the redundancy principle, the signalling principle, and the temporal and spatial contiguity principles.[8,16] The coherence principle states that unnecessary verbal or visual information should be eliminated because it disrupts schema formation and induces the learner to focus on the irrelevant information at the expense of the key information.[28,29] Although it has been shown that the learner's interest in the overall topic may help recall,[30–32] there is substantial evidence to suggest that when that 'interesting' information is irrelevant, it impairs the learning of key information.[25,29,33]

Also intended as a guideline for reducing extraneous processing, the redundancy principle warns that presenting the same verbal information simultaneously in both aural and visual modalities overloads learners' cognitive capacity because they expend unnecessary effort to process and reconcile both sources of verbal information; thus, narration should not be replicated with identical on-screen text.[25,34]

The signalling principle suggests that essential material should be highlighted through the use of headings and clear structural indicators, which are cues that help learners focus their attention on only relevant processes rather than using mental resources to attempt to independently discover the structure of a lesson.

Table 1 Evidence-based multimedia learning principles and their prevalence in medical animations (n = 430 unless otherwise noted)

Learning principle	Definition	Animations exhibiting principle, %	Recommendations for animation selection and design
Managing essential processing			
Pre-training principle	Relevant information is presented before the animation	7.7	Provide a glossary of key terms that will be used in the animation
Modality principle	Words accompanying an animation are presented aurally instead of visually	17.4	Present spoken text to augment visual content
Minimising extraneous processing			
Coherence principle	Animation contains only educationally relevant pictorial and verbal information	67.2	Eliminate background music, unrelated or unnecessarily flashy graphics, even if they appear interesting
Redundancy principle	On-screen text does not duplicate narration	45.6	Rely on narration to communicate verbal information If on-screen text must be used, present as labels rather than sentences
Signalling principle	Cues prompt learners to the organisation of essential material	18.9	Prior to the animation, provide an outline of the content If the animation describes steps, list them all first before repeating and elaborating on each one
Temporal contiguity principle	Visual elements are synchronised with corresponding narration	76.5*	Synchronise the timing of the animation with corresponding words in the narration
Spatial contiguity principle	Labels are placed close to visual elements	92.4†	Place labels on or next to associated images
Facilitating generative processing			
Interactivity principle	Learners control the order, pace and other interactive elements of the animation	61.2‡	Allow learners to pause, navigate through different segments of the animation, and manipulate parameters (e.g. rotate body part, zoom in/out)

* Percentage of the 306 animations with narration
† Percentage of the 328 animations with labels
‡ See Table 2 for details

The temporal contiguity principle states that narration should coincide with the appearance of relevant visual elements.[35,36] The spatial contiguity principle suggests that annotations or labels should appear next to corresponding graphics.[37] Adherence to these principles helps learners to reduce the unnecessary mental processing involved in trying to match segments of information that are far apart in time or space, and thus leaves more cognitive resources available for generative processing.

One principle that facilitates generative processing is the interactivity principle, which states that learners should have control over what occurs next on the screen.[8,38,39] An interactive environment helps learners engage in the material and generate coherent mental models to facilitate understanding.[27] As Table 2 shows, there are many different ways for learners to interact with their environment. For example, learners may be able to control when and where labels appear on screen (Fig. 1a), select part of the image to simultaneously view a global and focused perspective of anatomy (Fig. 1b), rotate an image for a more complete view, or manipulate the transparency or visible layers of an image (Fig. 2). Interactivity, almost by definition, also means that the lesson will be learner-paced, which allows the learning situation to be tailored for each individual. As noted

Table 2 Interactivity elements in reviewed animations (n = 430)

Interactivity principles	Total animations, %	Breakdown of total, % Computer-driven	Learner-driven	Computer- and learner-driven	Link to example (further instructions or time observed in parentheses)
Annotation/labels					
With overall on/off feature	40.9	1.4	39.5	0	http://getbodysmart.com/ap/muscularsystem/legmuscles/rectusfemoris/tutorial.html
Arrows/pin-point	65.3	24.4	25.3	15.6	http://getbodysmart.com/ap/nervoussystem/supportcells/satellitecells/tutorial.html
Individual labels*	81.1	36.0	19.5	25.6	http://www.argosymedical.com/Skin/samples/animations/The%20Skin%20Healthination/index.html
Progression of animations	100.0	56.7	4.9	38.4	http://www.understandspinesurgery.com/Animations (click Spine Conditions, then Degenerative Disc Disease)
Rotation of animations†	59.3	31.6	5.6	22.1	http://www.bmc.med.utoronto.ca/anatomia/intro.swf (click Larynx, then Structure & Function)
Transformation of visual elements¶	31.4	29.3	0.5	1.6	http://www.bmc.med.utoronto.ca/anatomia/intro.swf (click Orbit, then Digital Dissection)
Display layers of anatomical regions					
Transparency (see through)†	69.3	66.0	1.2	2.1	http://www.hybridmedicalanimation.com/work/animation/hybrid-interactive-heart/
Peel-back/Cut-Away‡	62.8	57.9	2.8	2.1	http://getbodysmart.com/ap/muscularsystem/wristhanddigits/extensordigitorum/tutorial.html
Speed control	24.5	3.7	19.1	0.7	http://www.bmc.med.utoronto.ca/anatomia/intro.swf (click Larynx, then Structure & Function)
Highlight region/parts					
With on/off feature	19.8	1.2	18.6	0	http://catalog.nucleusinc.com/display_interactive.php?movie=http://hamlet.particleweb.com/flvs/nucleus_remix/nucleusPlayer_sequel.swf&name=ProgressionofAtherosclerosis&title=Progression%20of%20Atherosclerosis&width=720&height=500&bgcolor=ffffff
With colour	73.5	63.7	8.4	1.4	http://www.argosymedical.com/Nervous/samples/animations/Serotonin%20Pathways/index.html (0:30)
Outline	17.9	15.1	1.9	0.9	http://www.understandspinesurgery.com/Animations (Spine Procedures, then TLIF; Step 1)
Drag and drop	7.6	0.2	7.4	0	http://www.bmc.med.utoronto.ca/anatomia/intro.swf (click Orbit, then Structure & Function, then Eye Movements)
Transition between global view and detailed view	80.2	74.7	4.9	0.7	http://getbodysmart.com/ap/circulatorysystem/blood/rbcs/functions/tutorial.html

Table 2 Contiuned

Interactivity principles	Total animations, %	Breakdown of total, % Computer -driven	Learner -driven	Computer- and learner-driven	Link to example (further instructions or time observed in parentheses)
Shrink/expand	42.1	34.4	3.5	4.2	http://getbodysmart.com/ap/muscletissue/contraction/couplingintro/tutorial.html (click right arrows, then 'contraction')
Simultaneous display of global view and focused view[§]	25.7	22.6	2.6	0.5	http://getbodysmart.com/ap/circulatorysystem/blood/rbcs/functions/tutorial.html (click hemoglobin)
Direct manipulation of animations by entering parameters	1.9	0.5	1.4	0	http://getbodysmart.com/ap/muscularsystem/wristhanddigits/extensordigitorum/tutorial.html
Fly-through	34.2	33.5	0.5	0.2	http://www.argosymedical.com/Other/samples/animations/Process%20of%20Hearing/index.html (0:10)

* See also Fig. 1(a)
† See also Fig. 2
‡ See also Fig. 3
§ See also Fig. 1(b)
¶ e.g. A healthy cell turning abnormal

previously, self-paced learning can minimise the negative effects of other adverse learning conditions (e.g. presenting visual verbal instead of aural verbal information)[26,27] and is therefore a highly important component of instructional animations.

Although CTML has guided research into the educational effectiveness of animations in various contexts and has even been specifically suggested as a basis for developing medical animations,[16] few studies have examined existing animations using multimedia learning principles as a lens for critical review. We applied the eight principles discussed here to our assessment of medical animations. Because the body of medical animations is large and their use in educational settings is widespread, we restricted our review to those animations that were publicly accessible to educators and students. Although there are many sources of paid-for animations that may provide a product that is somewhat different from free animations, we believe it is more likely that educators and students would seek free sources of information first. In addition, many of the free animations we reviewed were samples from companies that produce paid-for animations and thus it is likely that they present examples representative of products that are sold commercially. We believe our review of animations will help inform educators of the possible limitations of existing animations, with the ultimate goal of improving the quality of animation design in medical education. Therefore, increasing educators' awareness of key instructional design principles that guide animation design may result in a more critical appraisal and selection of appropriate animations for meeting instructional needs.

METHODS

In order to compile medical animations that are freely and publicly available online, we conducted Google (http://www.google.com) searches using the keywords 'medical', 'medicine', 'animation' and 'visualisation'. A biomedical librarian conducted the searches using different combinations of the keywords and saved the first 15 Google pages returned from each search. The librarian scanned all web links, noted pertinent animations using Google Bookmarks, and saved the search results under a Google account that was created to archive web links for reviewers' access. This search approach yielded a total

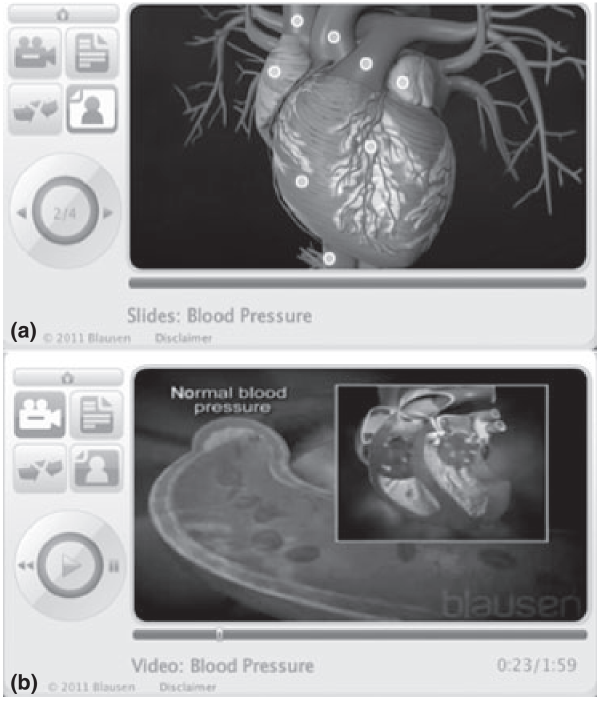

Figure 1 Blood pressure, Blausen Medical. (a) Users click on indicated dots to display labels. (b) Picture-within-picture feature for comparing global and detailed views. (Image courtesy of Blausen Medical Communications, Houston, TX, USA. Animations also available as mobile apps)

of 4455 animations made available by 60 unique websites.

Animations were included if the content dealt with basic sciences (e.g. physiology or anatomy), pathophysiology of disease processes (e.g. cancer development), or surgical interventions or medical procedures (e.g. anterior hip replacement). An animation was excluded from review if:

1 its content did not address a medical domain;
2 its duration was < 30 seconds, which was regarded by the review team as insufficient to convey critical information (30 seconds is the shortest animation duration in empirical studies of CTML[35,36] and is thus an appropriate baseline parameter for our analysis);
3 its text, such as annotations or labelling, was the sole animated object and no dynamic images or graphical elements were included;
4 its primary purpose was to market a medical device or drug;
5 it included a text watermark (i.e. 'Sample' or 'Demo Only') that obstructed reviewers' views, or
6 it was a stand-alone entity without the context of a hosting site, such as a YouTube video.

When these criteria had been applied, a total of 860 animations from 20 different developers were retained for review. The earliest date of original production was 2009; most animations had a more recent copyright date, suggesting their content had been updated since their original production. There were no detectable differences between animations produced in 2009 and those produced in later years. A team of five reviewers (a clinician-anatomist faculty member, a medical educator, a librarian, a graduate psychology student and an undergraduate biology student) collectively evaluated 10 randomly sampled animations for the purpose of building a consensus prior to engaging in an independent review. The

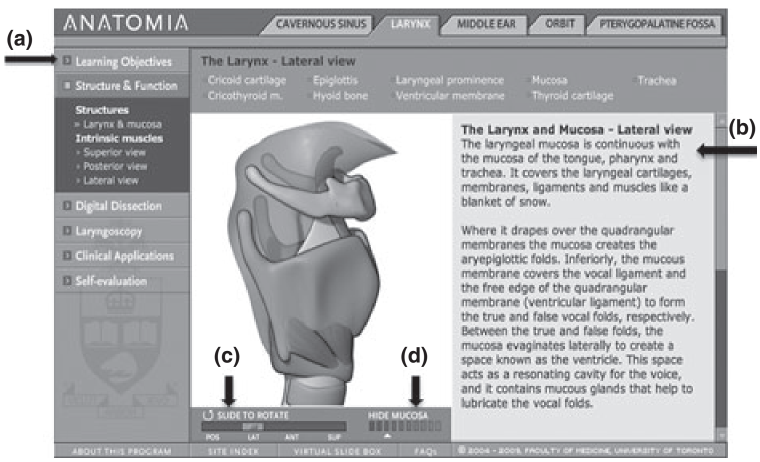

Figure 2 Anatomia, University of Toronto. The figure highlights (a) learning objectives, (b) teaching points, and two user-driven features for (c) rotating the portrayed animation and (d) controlling the transparency layers for viewing inner structures. (Image courtesy of Jodie Jenkinson. Copyright: Division of Anatomy, Faculty of Medicine, University of Toronto, Toronto, ON, Canada)

team then randomly sampled and reviewed 50% (n = 430) of the identified animations, ensuring that animations from all developers were included. Only half of the animations from the entire pool were reviewed for reasons of efficiency and practicality. The intent of our review was to be both comprehensive and feasible; we believed 430 animations was a large enough sample to reach a saturation point in detecting trends and variations in instructional techniques, especially given that we were able to examine animations made available by a wide range of developers. Of note, the pattern of results obtained in the initial analysis of 300 animations was very similar to that obtained at the conclusion of the study with 430 animations. Approximately 10% of the reviewed animations were then recoded by two of the reviewers to check for inter-rater reliability. These animations were randomly drawn from the total with the stipulation that the subsample should include animations that had been scored by each of the five original scorers and produced by each of the 20 developers. This rescoring, in addition to checking for inter-rater reliability, also helped control for reviewer fatigue and other biases that may have occurred during the original scoring process.

The data extraction sheet developed for reviewing animations was organised into three sections.

1 The profile of the animation hosting website included data on: (i) the name of the animation creator; (ii) the type of organisation with which the creator was associated (academic, commercial, government, non-profit); (iii) the focus of the animation (basic sciences, disease process/pathophysiology, procedure); (iv) the stated goal of the animation; (v) the source of animation content (clinical images, real-life photographs, graphics); (vi) two- or three-dimensionality of animated objects, and (vii) authoring software (Adobe Flash, Adobe Shockwave, etc.).
2 Multimedia learning principles: the presence or absence of eight multimedia principles in the reviewed animations was documented. In order to examine the interactivity principle, the team identified 13 distinct design elements that contributed to learner interaction (Table 2).[8,27,40]
3 Other features: (i) the duration of the animation (in seconds); (ii) full-screen capability, and (iii) social media features, such as user ratings or the option to share the animation via e-mail.

Review data were compiled into Microsoft Excel and data analyses were conducted using SPSS Version 20.0 (SPSS, Inc., Chicago, IL, USA).

RESULTS

Inter-rater reliability

Using the 10% of animations that were recoded by two reviewers, we compared the rescores with one another and with the original scores with Krippendorff's alpha to assess for reliability within and among raters. The alpha coefficient was 0.82, indicating a high level of consistency;[41] thus, original scores were used for all analyses.

Profile of the animation hosting websites

Of the 430 reviewed animations, most originated from commercial sources (79.8%), followed by academia/academic medical centres (4.9%) and others (e.g. private health care providers and non-profit organisations, 15.3%). The majority of animations (94.4%) used solely graphic images; very few (5.6%) included clinical images or real-life content. The content was divided into illustrations of basic sciences (40.2%), disease processes/pathophysiology (33.0%), medical procedures/surgical interventions (25.1%) or a combination (1.6%). Adobe Flash was the predominant tool (88.6%) used for creating animations, which were rendered largely in 3-D (75.3%) rather than 2-D (18.4%) or a combination (6.3%). Overall, the animations adhered to an average of 4.2 principles, or about half of the core principles we examined.

Managing essential processing: pre-training and modality principles

The third column of Table 1 summarises the percentage of animations that implemented each principle. The pre-training principle was the least implemented of the eight multimedia learning principles, with definitions of key terms and concepts appearing prior to the main lesson content in only 7.7% of the animations.

Only 17.4% exclusively used voiceover narration without text in accordance with the modality principle. The majority of the animations (74.9%) relied on written text in conjunction with images. We also noted a handful of animations (7.7%) that used images alone, without providing any verbal information.

Minimising extraneous processing: coherence, redundancy, signalling and contiguity principles

Approximately one third (32.8%) of animations violated the coherence principle by including unnecessary textual, visual or auditory elements that might cause extraneous processing. In violation of the redundancy principle, 54.4% presented text identical to and simultaneously with the narration.

The signalling principle was adopted to a limited degree: 73.0% of the animations included a descriptive title or header, but only 18.9% prompted learners at the beginning of the animation with an outline of the lesson's structure, and only 8.8% included explicit labels of the intermediate steps or segments (e.g. 'Step 1: Prepare the surgical site'; 'Step 2: Make an incision').

In terms of how visual elements of an animation were presented in relation to audio and other visual elements, the temporal and spatial contiguity principles were relatively well applied. Of the 306 animations with narration, 234 (76.5%) adhered to the temporal contiguity principle by synchronising the timing of the narration with the on-screen appearance of relevant images. The spatial contiguity principle was the most commonly implemented of the eight principles; of the 328 animations that used labels, 303 (92.4%) presented those labels next to relevant images.

Facilitating generative processing: interactivity principle

At least one interactive element was present in 61.2% of the animations. Table 2 summarises the percentages of animations that included interactive design elements and provides links to representative animations that contain each element. The data associated with the 13 originally defined features were broken down according to whether these features were predominantly computer-driven, learner-driven, or both. With the exception of a few features, computer control far outweighed learner control. The three exclusively learner-controlled elements related to textual labels were the ability to turn all labels on/off at one time (39.5%), clicking to pop up an arrow connecting a textual label and a visual component (25.3%), and clicking to reveal individual labels (19.5%) (Fig. 1a). Elements with a combination of learner and computer control included links or arrows that directed the animation's progression (43.3% combined) and allowed the rotation of certain visual components of the animation (27.7% combined) (Fig. 2). Learners tended to have little control (either exclusively or combined with computer control) over transformations of visual elements (e.g. a healthy cell becoming cancerous; 2.1% combined), increasing/decreasing image transparency to reveal structures at different levels (3.3% combined) (Fig. 2), or revealing cut-away images of anatomical layers (4.9% combined) (Fig. 3).

Other features

When computer-paced, the mean ± standard deviation duration of animations was 100.3 ± 59.7 seconds. Full-screen capability was offered in 16.7% of animations, and social media features such as user ratings and sharing were available in 28.1% of animations.

DISCUSSION

Our review of 430 publicly available medical animations revealed that these animations tended to be

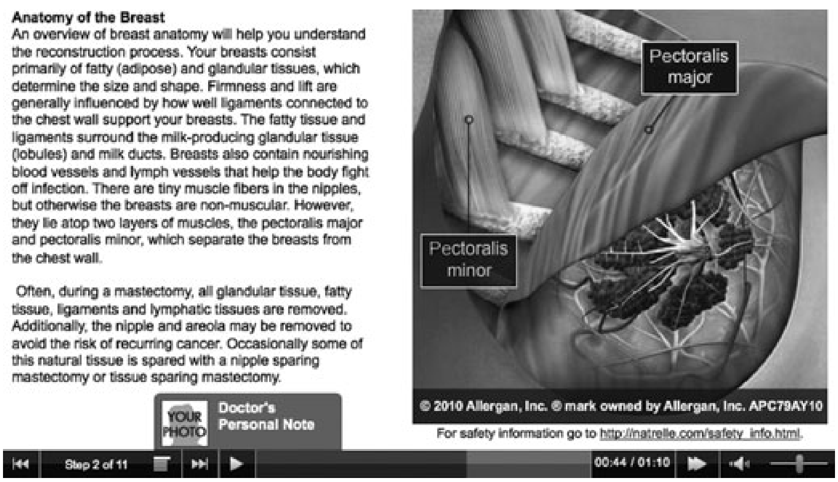

Figure 3 Breast reconstruction (Understand.com): illustration of teaching points accompanied by a computer-driven animation. The picture shows annotations displayed by the computer and a peel-back effect that reveals the underlying anatomical structure. (Image courtesy of Understand.com™)

brief, 3-D, Flash-based graphical objects that illustrated various types of basic science-related, pathophysiological and surgical procedural content. They were, on average, about a minute and a half long, which is consistent with much of the materials used in research on multimedia learning, indicating that the principles of CTML can be applied to many medical animations. Although most animations adhered to at least one example of a multimedia learning principle, the principles were not implemented as fully as they could have been. For example, the principles for managing essential processing (pre-training and modality) were rarely implemented. Fewer than 10% of animations defined key terms prior to the lesson, and < 20% used narration as the primary means of communicating verbal information, indicating many missed opportunities for managing essential processing. With regard to the pre-training principle, however, it should be noted that many of these animations might not be used as stand-alone lessons. It is likely that instructors provide their students with the necessary knowledge before presenting the animation, making adherence to the pre-training principle within the animation less important. One recommendation, then, is for instructors to ensure that their students are familiar with the terminology that will be presented in an animation prior to viewing it. In particular, instructors could provide a brief overview of key terms prior to showing an animation, perhaps by verbally reviewing them or by having a pop-up list on screen.

We also found a high percentage of animations that could potentially trigger cognitive overload through lack of coherence or redundancy. More than two thirds of the animations contained at least one design element that could lead to extraneous processing (e.g. background music, distracting or irrelevant images), and more than half presented redundant text. Fortunately, improvements in this area are not difficult to make: unrelated content and on-screen transcripts or bullet points identical to the narration can simply be removed. Although it may seem desirable to have on-screen text replicate the key information in the narration, visual text presented in conjunction with narration should be minimised.[25] Therefore, instructors should limit their use of on-screen text in order to reduce extraneous processing and facilitate learning.

As noted in the Introduction, these recommendations apply strictly to animation design; in longer lectures, providing some irrelevant information (e.g. a humorous vignette) may give students a mental break and have little detrimental impact on learning. However, given the brief duration of a typical animation and the proven harmful effects of irrelevant information,[25,29,33] we recommend that such information be eliminated from medical animations.

Fewer than a quarter of the animations attempted to reduce extraneous processing by employing the signalling principle and providing an outline of the lesson. This result indicates clear room for improvement: instructors and animation designers can present a brief outline of the lesson prior to the main content of the animation. If there are multiple stages within the animation (e.g. steps of a surgical procedure), then each step should be listed prior to the animation and restated immediately before its description in the body of the lesson. Using such organisational signals in an animation will help learners focus on the essential information and understand how each step fits into the overall process.[29]

In our analysis, visual highlighting appeared concurrently with the relevant narration about 75% of the time, indicating several instances in which extraneous processing could be reduced through signalling and improved temporal contiguity. Spatial contiguity tended to be well implemented in animations with labels; thus, animation designers should continue to place annotations close to the images to which they refer.

With regard to facilitating generative processing through the implementation of the interactivity principle, learner control was generally limited to turning on and off highlighting features using colours, outlines or annotations. Figure 1(a), for example, illustrates a good use of interactive labelling: the learner is able to select which button to push to reveal a label and definition of a given area of the image. Such features were absent from the majority of animations, which consisted of linear videos and offered little control for learners to directly manipulate parameters or objects within the animation. As medical students, in particular, will ultimately be interacting with and even performing the kinds of procedure illustrated in these animations, we recommend an augmented use of interactive features that minimise passive learning and, instead, promote discovery and generative processing on the learner's part. One example of how interactivity might be increased can be seen in Fig. 2. This particular animation provides an excellent example of user interactivity to manipulate the degree of transparency for uncovering underlying anatomical structures, an interactive element that was learner-driven in < 2% of the animations. The slide bar at the bottom of the screen allows users to manipulate the image's transparency to simultaneously observe varying degrees of outer and inner layers of anatomy.

To our knowledge, this is the first reported review of publicly available medical animations evaluated according to existing multimedia learning principles targeting animations. We offer several recommendations for transforming the current designer-centric animations into learner-focused animations to make them more effective teaching tools:

1. prior to showing the animation, provide a glossary of terms that learners will require in order to fully understand key teaching points;
2. provide a brief outline of the structure of the animation as well as distinct headers for each step or segment;
3. present extensive verbal information via narration only, especially for computer-paced lessons;
4. synchronise the timing of narration with the appearance of features such as accent colours, outlines and text annotations, and
5. embed learner control features such as speed control, simultaneous presentations of global and focused anatomy to afford comparative views of macro and micro fields, the rotation of a structure to afford multiple perspectives, the option to peel off anatomical layers at the learner's pace, and the option to view a transformation from a normal to an abnormal state by allowing users to manipulate different physiological parameters.

Our study had several limitations. We did not test the educational efficacy of each animation because the scope of the review focused on the adherence of animations to various multimedia learning principles. In addition, we restricted our review to stand-alone animations, which comprise only one type of multimedia resource available with today's technology. Furthermore, our review did not include peer-reviewed articles as sources for identifying animations, which may have excluded notable examples that represent exemplar applications of multimedia learning principles. Finally, by limiting our searches and reviews to free animations found online, we excluded commercial animations available for purchase and animations available after a sign-up process, including those only available via an academic intranet.

Although we reviewed the presence of social media features, such as being able to 'share' the animation on Facebook, we are not aware of any research connecting these features to the interactivity principle as defined by CTML. Examining the extent to which social media features initiate similar types of processing or engagement as other interactive features would be a valuable avenue for future research.

It is interesting to note that some principles were frequently implemented (e.g. temporal contiguity), whereas others were very rare (e.g. signalling). This imbalance may represent a lack of communication between theoretical and applied approaches to multimedia learning, or even differences among the intuitive applications of the various principles. For example, experts and novices respond differently to some aspects of multimedia lessons,[34] but experts have substantial influence on the design of instructional animations. It may be that something that seems intuitive to an expert is not yet clear to a novice; therefore, providing an outline of steps to a surgical procedure may seem unnecessary to an expert surgeon designing an animation, but it does, in fact, noticeably aid a novice learner. For this reason, it is even more important to judge animations based on empirically established findings rather than on an intuitive sense of what seems appropriate.

As animations become increasingly common in educational settings, attention to empirically based principles is crucial to effectively guide students' learning of the complex mechanisms and processes involving the human body. An application of multimedia learning principles to the development of instructional animations will contribute to learners' construction of mental models and overall comprehension of the learning material.

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