



Principled animation design improves comprehension of complex dynamics



Richard K. Lowe^{a, b, *}, Jean-Michel Boucheix^b

^a Curtin University, Kent Street, Bentley 6102, Australia

^b University of Burgundy, Esplanade Erasme, 21078 Dijon, France

ARTICLE INFO

Article history:

Received 17 June 2015

Received in revised form

26 May 2016

Accepted 26 June 2016

Keywords:

Animation design

Complexity

Animation processing model

Mental model acquisition

Composition approach

ABSTRACT

Learners can have difficulty in decomposing conventionally designed animations to obtain raw material suitable for building high quality mental models. A composition approach to designing animations based on the Animation Processing Model was developed as a principled alternative to prevailing approaches. Outcomes from studying novel and conventional animation designs (independent variable) were compared with respect to mental model quality, knowledge of local kinematics, and capacity to transfer (dependent variables). Study of a compositional animation that presented material in a contiguous fashion resulted in higher quality mental models of a piano mechanism than non-contiguous or control (conventional) versions but no significant differences regarding local kinematics or transfer. Eye fixation data indicated that the compositional animation led to superior mental models because it particularly fostered relational processing. Implications for future research and the design of educational animations are discussed.

© 2016 Published by Elsevier Ltd.

1. Introduction

Animations have become a ubiquitous feature of technology-based learning materials (Höffler & Leutner, 2007). However it has also become clear that animation can be a two-edged educational sword (Lowe, 2014) - the undoubted benefits of animations must be weighed against the processing costs they may impose on learners (Lowe & Schnotz, 2008). The research reported here investigated a novel design approach for reducing such processing costs in order to better capitalize on animation's benefits.

Conventionally-designed animations that present complex subject matter to learners who are novices with respect to the depicted domain have proven to be particularly problematic. The difficulties learners experience with such depictions have been attributed to the very particular way in which they present their subject matter and the psychological consequences of those presentational characteristics. Prime amongst these characteristics is the dynamic nature of animations. While animations undoubtedly have a major advantage over static graphics in their direct, explicit presentation of spatiotemporal information, their dynamics can

also have negative effects on learners' extraction of crucial task-relevant information (Lowe, 2003). This is because when learners are faced with animations that portray complex, unfamiliar dynamic subject matter, many and varied simultaneously presented aspects of the animation compete for the learner's limited attentional resources (Lowe, 1999; Schnotz & Lowe, 2008). Unfortunately, the information learners extract tends to be what is perceptually salient rather than what is task relevant. Further, the information presented in an animation is intrinsically transitory so the time available for the learner to process it is very limited. This situation can be exacerbated when animations present rapidly changing subject matter at a realistic speed. In the next section, we summarize ways in which researchers have attempted to ameliorate these processing challenges.

1.1. Efforts to improve educational effectiveness

Researchers have investigated numerous interventions intended to increase animation's effectiveness as a tool for learning (Ploetzner & Lowe, 2012). They include giving the learner control over the animation's display regime (Boucheix, 2008; Lowe, 2004, 2008; Scheiter, 2014), modifying the animation's presentation speed (Boucheix, Lowe, & Bugajska, 2015; Fischer, Lowe, & Schwan, 2008; Meyer, Rasch, & Schnotz, 2009), subdividing the animation's

* Corresponding author. Curtin University, Kent Street, Bentley 6102, Australia.
E-mail addresses: r.k.lowe@curtin.edu.au (R.K. Lowe), Jean-Michel.Boucheix@u-bourgogne.fr (J.-M. Boucheix).

time course into smaller segments (Spanjers, Wouters, Van Gog, & Van Merriënboer, 2011; Wong, Leahy, Marcus, & Sweller, 2012), cueing the animation's high relevance information (De Koning, Tabbers, Rikers, & Paas, 2007; Lowe & Boucheix, 2011; Boucheix, Lowe, Putri, & Groff, 2013), providing strategy training to learners regarding more effective animation processing (Kombartzky, Ploetzner, Schlag, & Metz, 2010; Ploetzner & Schlag, 2013), accompanying the animation with ancillary learning activities (De Koning, Tabbers, Rikers, & Paas, 2010; Mason, Lowe, & Tornatora, 2013) and displaying multiple animation segments simultaneously (Ploetzner & Lowe, 2014; Rebetez & Bétrancourt, 2009). However, achieving major improvements in the quality of the mental models that learners develop from animations has proven to be particularly elusive (Boucheix & Lowe, 2010).

Although many innovative interventions have been pursued by researchers thus far, there is one key aspect that has not yet been addressed: the fundamental design assumptions upon which the animations are based in the first place. We suggest that some major problems learners currently have in processing animations could be reduced by a fundamental re-thinking of animation design. The research reported here investigated the potential of an alternative approach to designing educational animations. Rather than being primarily concerned with animations as *external* representations of the target subject matter (as is the case with conventionally designed animations), the main focus of this alternative is on helping learners to compose better *internal* representations (i.e., mental models) (Lowe, *in press*). Because of its concern with the psychological processes involved in composing these mental models, we have termed this design alternative the *composition approach*. In the study reported here, conventional and novel types of animation design (independent variable) were compared with respect to their outcomes for mental model quality, knowledge of local kinematics, and capacity to transfer (dependent variables).

1.2. Theoretical foundations for compositional animation design

The origins of the composition approach lie in the Animation Processing Model (APM) (Lowe & Boucheix, 2008). This theoretical framework describes the perceptual and cognitive processes that are thought to occur when an individual is engaged in learning from *conventionally* designed complex explanatory animations. We characterize these conventional animations as *comprehensive* representations because they portray the targeted aspects of their subject matter in a relatively comprehensive and faithful manner, thus following a “physical fidelity principle” which is known to impair learning especially for domain novices (Van Merriënboer & Kester, 2014). They include all the referent system's relevant entities and depict their dynamics in a behaviorally realistic manner (Lowe & Boucheix, 2012). The APM can be used to identify potential sources of learner difficulty in processing complex comprehensive animations and to suggest ways of ameliorating such difficulties.

As summarized in Fig. 1, the Animation Processing Model has five main phases. Overall, this learner processing can be divided into two broad types of activity: *decomposition* (APM Phase 1) and *composition* (APM Phases 2–5). A distinction is thus made between (i) analytic processing in which the learner must initially decompose the animation's continuous flux of information into the discrete event units (entities plus their associated behaviors) that provide the raw material for mental model building, and (ii) synthetic processing in which this raw material is cumulatively and iteratively composed into the higher order knowledge structures that comprise a mental model of the target subject matter.

Previous research indicates that decomposition of a complex animation can be particularly problematic for learners who lack domain specific background knowledge (Lowe & Schnotz, 2014).

Rather than decomposing the presented depiction appropriately into the thematically relevant event units required for building high quality mental models, learners tend to extract subsets of information on the basis of their perceptual salience (Schnotz & Lowe, 2008). The net result is that this unsuitable extracted raw material can severely compromise the quality of the mental models they are ultimately able to build from study of the animation.

The composition approach was devised with the intention of better matching the fundamental design of complex animations to the way learners process dynamic visualizations. It aims to remove a substantial barrier to acquisition of high quality mental models by relieving learners of the necessity to decompose comprehensive animations. Instead of having to carry out Phase 1 processing by themselves, learners are progressively ‘fed’ the total set of required information via a series of small, discrete portions that in one sense could be considered as a result of an ‘ideal’ decomposition. In terms of the APM, this essentially allows learners to by-pass error-prone Phase 1 processing activity and move straight to Phase 2 and subsequent processing involving the composition of dynamic micro-chunks into higher order structures. As explained later, practical implementation of the composition approach is particularly concerned with facilitating effective relational processing because of its importance to forming the hierarchically organized knowledge structures that are characteristic of high quality mental models.

Although the composition approach originated from the APM and is specific to learning from complex animation, it is consistent with a broader range of approaches that aim to facilitate complex learning and performance of complex tasks more generally (De Jong & Lazonder, 2014; Van Merriënboer & Kirschner, 2013). A key focus of research in this area is how instruction and tasks may best be sequenced (e.g., Van Merriënboer & Kester, 2014; Van Merriënboer, Kirschner, & Kester, 2003). Various alternatives are possible – for example, whole-part versus part-whole sequencing. Of particular relevance to the present investigation is the Sequencing Principle which indicates that “... it is often better to sequence learning tasks or complex pieces of information from simple to complex than to present them in their full complexity at once” (Van Merriënboer & Kester, 2014, p.116). It should be noted that in many cases, application of this principle implies that the material will need to be subdivided in some way in order that pieces are available to be sequenced.

A typical approach based on simple to complex sequencing is to break the material or performance into simple parts that are then trained separately and progressively combined into the whole (Van Merriënboer et al., 2003). Instructional sequencing has been used in a range of ways including with respect to information pre-training (Mayer & Pilegard, 2014; Mayer, Mathias, & Wetzell, 2002), element interactivity (Kester, Kirschner, & Van Merriënboer, 2004a, 2004b), and dynamic visualizations (Khacharem, Spanjers, Zoudji, Kalyuga, & Ripoll, 2012; Spanjers et al., 2011). Various studies have shown the positive effects of such sequencing techniques (e.g., Clarke, Ayres, & Sweller, 2005; Limniou & Whitehead, 2010; Mayer & Moreno, 2003; Mayer et al., 2002; Musallam, 2010; Pollock, Chandler, & Sweller, 2002).

However, the applicability of sequencing approaches can be highly specific. Sequencing may need to be implemented in very different ways depending on considerations such as the learning goal, the type of display, the subject matter involved and the learner's level of prior knowledge. For example, some types of sequencing appear not to be suitable for complex learning that requires coordination between parts, and the integration of knowledge, decisions and/or procedures (Naylor & Briggs, 1963; Van Merriënboer, 1997). In the case of complex comprehensive animations, it is clear that presentation of the subject matter as a whole can be very problematic for learners (Lowe & Boucheix,

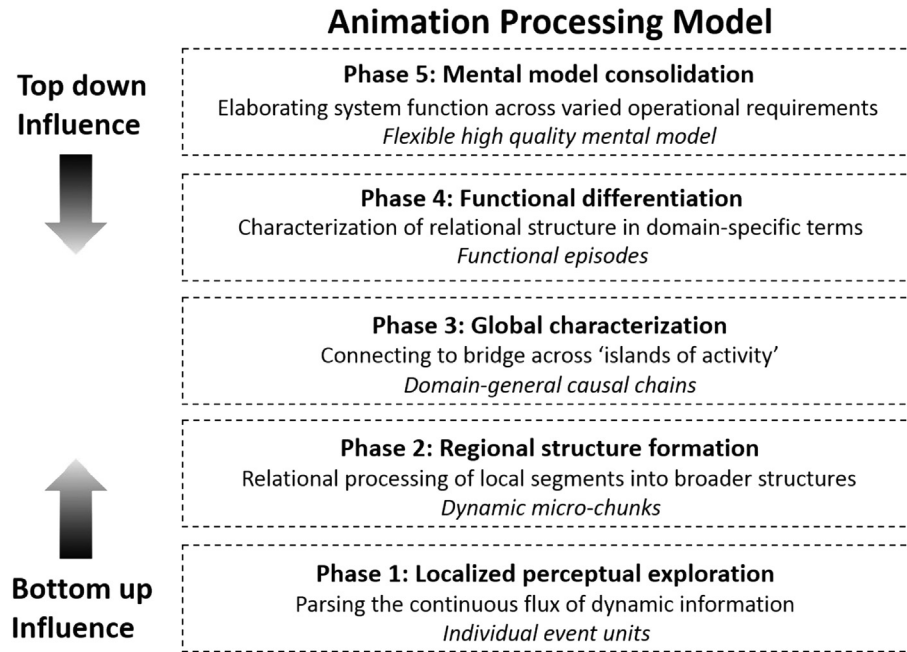


Fig. 1. Summary of Animation Processing Model main phases (Lowe & Boucheix, 2008).

2012). This suggests that the part-whole sequencing involved in the composition approach may be more effective than whole-part sequencing. The work of White and Frederiksen (1990) also has resonances with the composition approach. For these authors, the sequencing of complex learning tasks should be based on the progression of mental models supposed to be involved as the level complexity increases. In the composition approach, it is assumed that the cumulative, incremental processing posited by the APM as being the route to building a high quality mental model will be facilitated by helping learners form increasingly complex knowledge structures.

1.3. Subdividing and sequencing complex animations

The structure of the subject matter portrayed in an animation is an important consideration when contemplating how it might best be subdivided and sequenced. One hallmark of the subject matter depicted in complex animations is that it typically involves considerable *simultaneity*. Fig. 2 shows the mechanism of the complex mechanical device used in the present investigation – a traditional upright piano. A conventionally-designed comprehensive animation portrays the sophisticated operation of this mechanism with considerable fidelity. Throughout the animation's entire time course, the portrayal presents learners with not only the full set of the mechanism's various physical components, but also a close mimicking of the various movements that those components perform during the piano's operation (i.e., behavioral realism). These movements occur either simultaneously or in rapid cascades throughout the duration of the mechanism's complete operational cycle and take place in locations that are widely distributed across the display area.

The APM identifies these simultaneous or near simultaneous movements of distributed entities as a challenge to learners because of the competition for visual attention they engender due to limitations of the human information processing system.

One possible way to subdivide an existing comprehensive animation is to slice its time course into pieces, an approach described as *segmentation* (Spanjers, Van Gog, & Van Merriënboer, 2010). The

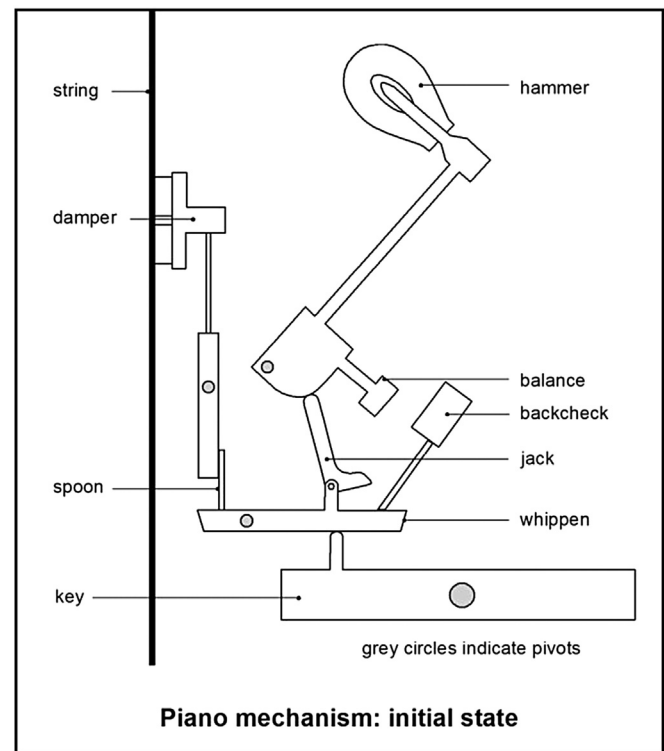


Fig. 2. Frame from a comprehensive animation of a piano mechanism's operation.

segments thus produced can then be played one at a time (separated by suitable pauses) and in a sequence corresponding to their order in the original unsegmented animation. This segmentation approach is likely to be most successful for animations that depict subject matter in which individual events occur in a straightforward linear temporal sequence (i.e., with little or no simultaneity). In such cases, careful slicing of the animation into meaningful

segments results in 'stand-alone' subsets of the subject matter that place fewer demands on learner processing (e.g., Wong et al., 2012). However, segmentation can be problematic when the subject matter depicted in an animation contains extensive simultaneity, especially if the simultaneously occurring events are staggered. This is because slicing through the animation in an effort to separate out one coherent event will likely disrupt the coherence of other co-occurring events. According to the APM, it would be counterproductive in terms of the learner's attempts to build a high quality mental model because such building activity is essentially about composing coherent hierarchical knowledge structures.

The composition approach uses a form of subdivision that appears to be more suitable for animations in which there are multiple co-occurring events (i.e., substantial simultaneity). Under such circumstances, a more 'forensic' approach is required that minimizes the type of collateral damage to coherence described above. Rather than slicing up the animation at intervals along its time course, subdivision is based on separating out intact individual event units by a detailed analysis of the subject matter's spatio-temporal structure. An example of such an event unit analysis for the piano mechanism is given in Appendix A. The subdivision approach used is somewhat analogous to that used in post-mortem examinations where it is vital to retain the coherence of multiple individual bodily sub-structures co-occurring in the same space. Because the body is not a simple linear structure, slicing through it as a whole (rather than isolating its component sub-structures) would compromise a proper understanding of the cause of death.

1.4. Implementing a composition approach

As noted, design of a compositional animation begins with a detailed content-specific analysis which systematically teases out all the subject matter's relevant event units, characterizes their natural temporal arrangement, and reveals information about simultaneity. This analysis can then be used along with detailed subject matter knowledge and the APM as a basis for considering other key issues, such as the causal chains involved, the functional relationships between event units, and potential processing problems that learners may encounter if faced with a comprehensive animated presentation of the subject matter. Because the intention of the composition approach is to better align animation design with processing activities identified by the APM, a crucial aspect of implementation is how sub-sets of the total information required for building a mental model are chosen and presented to the learner. The main focus of the present investigation was on issues associated with more bottom-up phases of animation processing. A primary goal was to relieve learners from the burden of decomposing a comprehensive representation of the subject matter, as identified in Phase 1 of the APM, by supplying them with optimal 'ready-decomposed' material. However, we also aimed to provide such material in a way that facilitated learners' later compositional processing in which subordinate information components were progressively and hierarchically accumulated into more inclusive knowledge structures.

The analysis described above identifies the subject matter's individual event units that constitute the fundamental raw material required for internal composition of a mental model. However, it does not specify how this information should be presented to the learner in order to facilitate its extraction and processing by the learner. Consideration of the APM suggests that three aspects are likely to be particularly important here: the size of the information packages presented to the learner (i.e., the number of event units delivered at once), the nature of those information packages (i.e., their propensity for being interconnected), and the sequence in which information packages are presented. For the current

investigation, our compositional animation presented learners with just two event units at a time. We term these pairs *relation sets* to indicate that their constituent event units are intimately related by a functional relationship involving their direct interaction. Examples of relation sets used in the present investigation are given in Fig. 3.

Part of our rationale for using relation sets consisting of pairs of event units is that it takes account of working memory limitations and so helps avoid possible problems such as excessive cognitive load. However, a pair is also the minimum grouping required to furnish learners with a localized and functionally related set of event units. This means that our externally presented relation sets approximate the internally represented *dynamic micro chunks* identified as the main actors in learners' Phase 2 APM processing. These relation sets were also constituted with event units in common order to allow their ready inter-linkage. As such, they should be well suited for further iterative and cumulative processing as occurs in subsequent APM processing phases. The final consideration was the issue of how delivery of relation sets should be sequenced. Bearing in mind that our aim was to foster composition of relation sets into superordinate spatiotemporal structures, we based their sequencing on the two main overarching causal chains responsible for the piano mechanism's operation (i.e., the key-hammer and key-damper causal chains).

1.5. Contiguous versus non-contiguous presentation

The composition approach to designing animations takes into account not only the amount of information presented to learners at one time, but also the potential of the chosen information subsets to promote relational reasoning. The sequence of relation sets presented in this approach will be termed *contiguous* to indicate their relational continuity. In an effort to determine if not only size but also relation-forming propensity are important, we also devised a different form of sequential presentation that used paired event unit groupings that were not directly related to each other via inter-entity contact (i.e., *non-contiguous*). For example, instead of being immediately adjacent components of the causal chain (such as the key and the whippen), the entities were separated from each other (such as with the key and the hammer). Further, the pairs were not sequenced logically in terms of causal chain progression, but rather were presented in a non-optimal quasi-random order. This non-contiguous type of presentation should prejudice learners' attempts to build higher order knowledge structures by making it more difficult to establish how the event units comprising each of the pairs were related and what relations might be at work between successively presented pairs.

1.6. Research questions and hypotheses

The present research addressed two overarching questions concerning the independent variable (animation design):

- (i) Does a contiguous animation designed according to the composition approach help learners to build better mental models of complex subject matter than non-contiguous or conventionally-designed animations?
- (ii) How does learner processing of a contiguous compositional animation differ from the processing of non-contiguous or conventionally-designed animations?

Three dependent variables used to assess the learning outcomes were; (i) the quality of mental models developed, (ii) knowledge of the studied piano mechanism's local kinematics, and (iii) capacity to transfer.

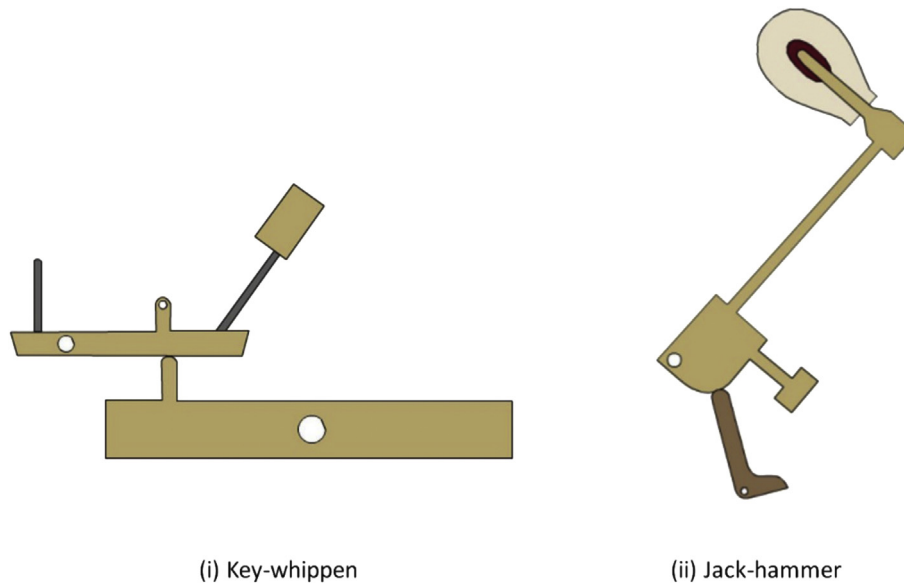


Fig. 3. Two different example relation sets from a compositional animation of the piano mechanism. Each consists of a pair of directly interacting event units: (i) key-whippen relation set (ii) jack-hammer relation set (see also Fig. 1).

Hypothesis 1. Participants in the contiguous condition would construct higher quality mental models than constructed by those in either the control or non-contiguous conditions. This is because the sequenced relation sets in the contiguous version of the animation facilitated both the building of relevant dynamic micro chunks and the optimal linkage of these chunks into the superordinate knowledge structures that are characteristic of high quality mental models.

Hypothesis 1A. Participants in the contiguous condition would exhibit better performance on a transfer task than those in the other two conditions. This is because a higher quality mental model of the original mechanism would provide participants with a functional level representation of the device's operation that could not be achieved by those whose mental models were of lower quality. Having a functional representation of the original system should facilitate a participant's mapping and generalization to another mechanism of the same category and their building of a mental model for its operation.

Hypothesis 2. Participants in the contiguous, non-contiguous and control conditions would achieve similar scores on a measure of local kinematics (i.e., movements of the individual entities comprising the animated mechanism). Local kinematics scores would not be expected to differ across conditions because they concern only the behavior of each of the entities in its own right and not the relationships between two or more entities.

Hypothesis 3. The potential benefits of a compositional animation versus other designs should be reflected in the patterns of eye fixations that occur during viewing. Previous literature has related longer fixations to deeper processing, including particularly relational processing, while high numbers of fixations have been attributed to less efficient search and more superficial processing (Godberg & Kotval, 1999; Holmqvist et al., 2011; Hyona, 2010). Fixations for a contiguous animation should therefore be fewer and longer than for a conventional comprehensive animation. Further, the pattern of fixations for a non-contiguous animation would be expected to reflect the difficulty in establishing how the presented fragments are related. In this case, fixations should also be more frequent and shorter than for the contiguous version.

2. Method

A one factor, between subjects experimental design was employed with three conditions, each using a differently-designed animated version of the same piano mechanism subject matter: (i) contiguous (compositional), (ii) non-contiguous, and (iii) control (comprehensive).

2.1. Participants

Sixty undergraduate students from a French university participated in this study (20 students per condition). The mean age was 21.08 years, with 76% being female. Preliminary testing showed that none of the participants had prior knowledge of how a piano mechanism works. Participants were randomly assigned to the three experimental conditions.

2.2. Materials

2.2.1. The animations

A frame from the comprehensive version of the piano animation material is shown in Fig. 4 (see Lowe & Boucheix, 2008; Boucheix & Lowe, 2010 for further details). There was no explanatory text accompanying the animation. However, labels could be made to appear before and after the study period by mouse-over on a particular entity.

The piano mechanism operates by way of two coordinated causal chains, one involving the operation of the damper and the other involving the operation of the hammer. Each of these causal chains is made up of a succession of component pairs whose physical interaction propagates motive force from the initial cause (a player pressing the piano key) to the two interrelated effects (removal of the damper from the piano string and the striking of that string by the hammer to produce a musical note). When this mechanism operates, one set of simultaneous and rapidly cascading events propagates the causal chain by which a press on a piano key results in the hammer striking the string to produce a musical note. At the same time, another set of co-occurring events removes the damper so the string is free to vibrate when struck by

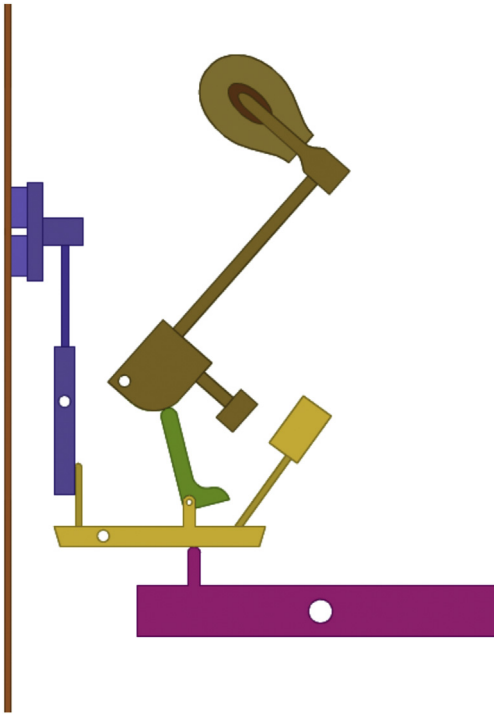


Fig. 4. Example frame from the comprehensive animation. Entities were colour-coded to facilitate identification during mental model quality assessment task.

the hammer. Similar sets of simultaneous events take place during the subsequent stages by which the piano mechanism is paused then reset ready for the next operational cycle. Such an animation is likely to make severe demands on learners' visual processing capacity.

2.2.2. The control condition: a comprehensive animation

This condition presented a conventional comprehensive animation of the piano mechanism with all components present and behaving in a veridical manner (see Fig. 4).

2.2.3. The contiguous condition: a compositional animation

This condition presented a succession of relation sets sequenced according to the progression of causal chains through the piano mechanism. A small initial portion of this sequence is represented by Fig. 5. First, a mini-animation consisting of the key/whippen relation set would be shown (Fig. 5, bottom left). Next, it would be replaced (via fade transitions) by another mini-animation showing the whippen/jack relation set in operation (Fig. 5, bottom right). The expectation was that the learner would use the whippen event unit that is common to both these mini-animations as the link between them that allowed a superordinate key-whippen-jack relation to be composed from these two successive presentations (Fig. 5, top centre). This type of progression from relation set to relation set would continue along the course of the causal chains until all aspects of the mechanism's operation (from initial key press to ultimate sounding of the musical note) had been covered. In this approach, the learner is confronted with much less information to process per unit time than would be the case for a conventional comprehensive animation. Further, the information that is presented is far less distributed across the display area and the simultaneity of events is greatly reduced. Systematically sequencing the presentation of relation sets that are involved, progressively from cause to effect, should facilitate their efficient and accurate composition into the desired higher order structure.

2.2.4. The non-contiguous condition: limited size but difficult to relate

This condition presented a succession of pairs of event units that were neither in direct contact nor with an event unit in common. Further, these pairs were delivered in a quasi-random sequence with the proviso that no two successive relation sets were presented in the same order as they would occur within the causal chain. Two example pairs from this condition are shown in Fig. 6.

As with the contiguous condition, these pairs were displayed as a series of mini-animations punctuated by fade transitions. This form of presentation continued until the same total coverage of event units was achieved as had been the case for the contiguous condition materials. Once again (as in the contiguous version), the learner is confronted with much less information to process per unit time than would be the case for a conventional comprehensive animation. The simultaneity of events is again greatly reduced. However, there are not the same relational affordances that exist in the contiguous condition. The two event units in each pair are indirectly (rather than directly by contact) related and the quasi-random presentation sequence should impede rather than facilitate their efficient and accurate composition into the desired higher order structure.

2.3. Measures and data analysis

2.3.1. Comprehension post-tests

Because the main goal of the composition approach to animation design is to help learners build higher quality mental models, its primary emphasis is on facilitating the relational processing that learners need to carry out in order to construct the required superordinate knowledge structures. The approach therefore targets how entities interact with each other rather than the dynamics of individual entities *per se*. This difference in targeting should be reflected in the extent to which relationships versus entity dynamics are processed by learners. The three tasks used in comprehension post-testing are described below.

2.4. Cross movement task

The *cross movement task* provided a less mediated measure of knowledge of movements than is possible using standard approaches such as verbal questions. It required participants to physically produce the movements of the piano mechanism's components (Boucheix et al., 2013). At the end of the learning session, a static picture of the piano mechanism in its initial state was displayed on the computer screen. A red cross was positioned on a part of a component. The learner was told to "use the mouse in order to move the cross to the correct final position it occupies when the key is pressed". Participants were required to demonstrate the movements for stages one (striking), two (rebound), and three (reset) of the piano mechanism's operation. In total, each participant performed the cross movement task twenty five times with the cross being at a different position on every occasion. The order in which the crosses were presented (within each stage of the piano mechanism) was randomized across participants. For each of the piano mechanism's components, several different cross positions were involved but with only one cross displayed at a time. Performance of this task was assumed to require a mental simulation of the dynamics of each local component of the piano mechanism in order to infer movements of the parts shown in the provided static picture. For each position of the cross, the entire movement of the mouse made by the learner was registered by the computer in real time. The angular direction of the movement and its amplitude were subsequently calculated and performance scored by comparison with the actual motion of the component as

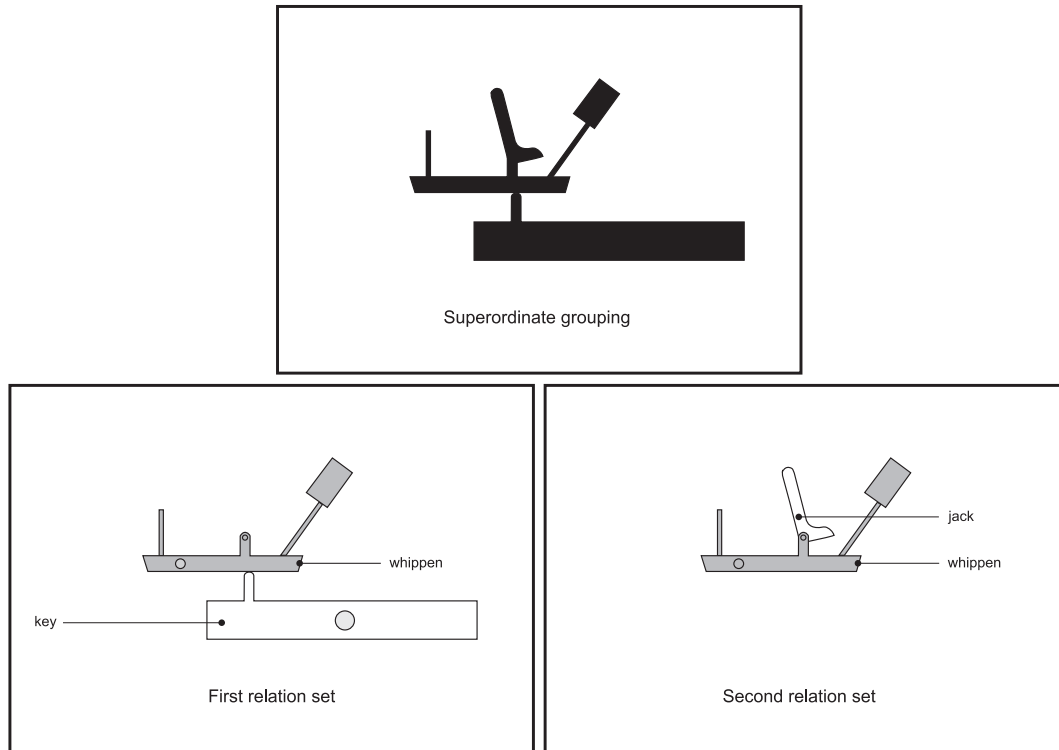


Fig. 5. Example Contiguous relation sets. Note (i) contact relationship between event units in each relation set (key-whippen; whippen-jack), (ii) adjacency of successive relation sets, (iii) sharing of event unit (whippen) between the two relation sets. Sequencing and constitution of relation sets facilitates composition of the hierarchical structures necessary for building high quality mental model.

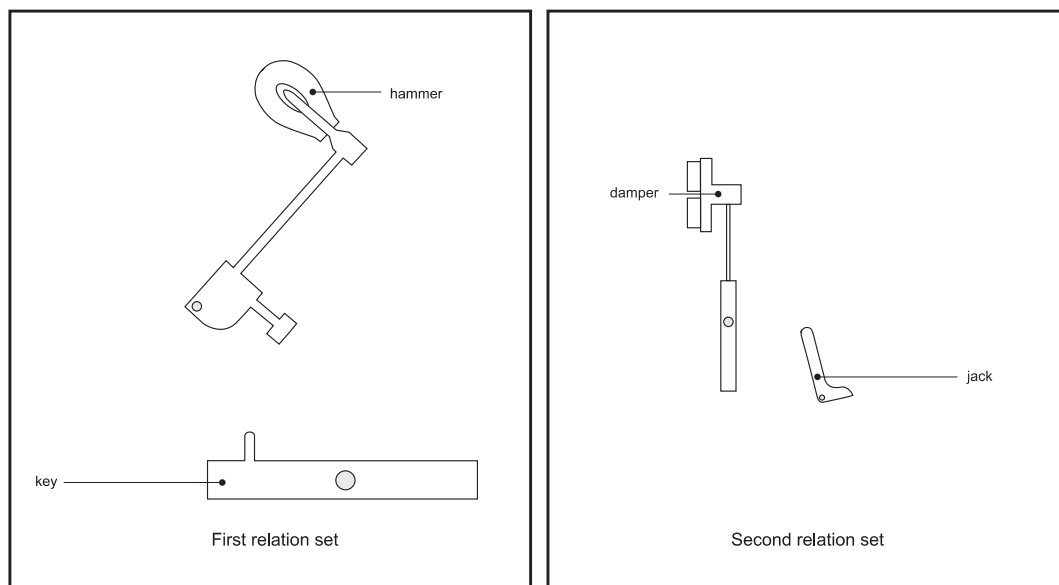


Fig. 6. Example Non-Contiguous pairs. Note (i) no contact relationships between event units in each pair, (ii) separation of pairs, (iii) no sharing of event units between two pairs. Prejudicial to building higher order knowledge structures.

depicted in the animation (angular direction - 1 point; amplitude - 1 point). Total scores out of a possible maximum of 50 points (according to the degree of correspondence with regard to angle and distance) were calculated and converted to percentages. These scores were assumed to reflect the internal representation of the animation's local kinematics.

2.5. Mental model task

For the *mental model quality task*, participants were asked to “write as much as you can about what happens with all parts of the system when someone presses the key down and then releases it”. In order to avoid difficulties related to the recall of technical names of the components, participants were also given a sheet of paper

upon which labeled pictures of the piano components were shown in random positions. Mental model scores were derived from participants' written protocols describing operation of the piano mechanism. This was done by coding the protocols using an established checklist to assess the quality of the mental model (see Boucheix & Lowe, 2010). The scoring guide for functional mental-model-quality (with respect to its appropriateness, accuracy and completeness, Lowe & Schnotz, 2008) was based on the 15 micro-steps constituting the three main stages of a piano mechanism's functioning (see Appendix B). Each correct micro-step was awarded one point if fully and accurately reported or half a point if reported only in part. For each micro-step incorrectly reported, half a point was deducted from the score. Participants' answers were rated by two independent raters, with inter-rater agreement, chance corrected Cohen's kappa, being 0.92. Overall mental model scores were also transformed into percentages of the total possible score of 15 points.

2.6. Transfer task

Participants also undertook a *transfer task* in which they were given a single static depiction of a novel piano mechanism (Fig. 7) and asked to demonstrate its components' movements via a cross task (as above). It was assumed that in order to perform the required cross task demonstration of the transfer piano mechanism's components, learners would rely on the mental model they earlier constructed while viewing the original piano animation. Although in the strictest sense the cross task addresses only the movements of each individual entity in isolation, in the particular case of this transfer task it would have broader implications. This is because there was no animated version of the novel piano from which participants could have extracted such information fragments. Rather, the movements generated would probably be based on learner inferences made on the basis of fundamental dynamic relationships that were present in the mental models they constructed from the original piano mechanism animations. On this basis, we contend that transfer task scores are indicative of mental model quality. Learners who developed a high quality mental model of the original piano mechanism should be able to 'see past'

the superficial characteristics of the novel piano mechanism to infer the dynamic relationships that would need to occur in order for it to perform the same musical operations as the original mechanism.

As was the case with the original piano mechanism used in the learning stage, data from the local kinematics task were compared with the actual movements of respective components of the transfer piano mechanism and given a percentage score according to the degree of correspondence with regard to distance and angle. However, because the transfer mechanism has fewer components, there were only sixteen crosses to be moved so the maximum possible absolute score was 32 points.

2.6.1. Eye tracking measures

During study of their allocated animation versions, all participants were eye tracked using a Tobii 1750, 50 Hz binocular corneal reflectance eye tracker. Data from two participants in each condition were excluded from the analysis because of low eye movement sample rate (less than 75%). Areas of Interest (AOIs) were defined for the six major components of the original piano mechanism (Key, Whippen, Jack, Hammer sub-system, Damper sub-system, and String). Each of these AOIs was defined with sufficient scope to include the boundaries of the particular piano part's entire movement during its operational cycle. A further Null AOI was established for all fixations that fell outside the six component-based Areas of Interest. The boundaries of the AOIs were set in such a way as to minimize areas of overlap between the AOIs due to component movements. Two indicators of participants' eye movement behavior were examined: (i) mean fixation duration (i.e., mean length of fixations during processing of the animation); (ii) fixation count (i.e., the total number of fixations made in the AOIs).

2.7. Procedure

Sessions for all three conditions began with delivery of instructions (60s) and presentation of a labeled static picture of the entire mechanism as an overview (30s). For the contiguous and non-contiguous versions, this was followed by presentation of four complete cycles of the piano mechanism's operation given in the

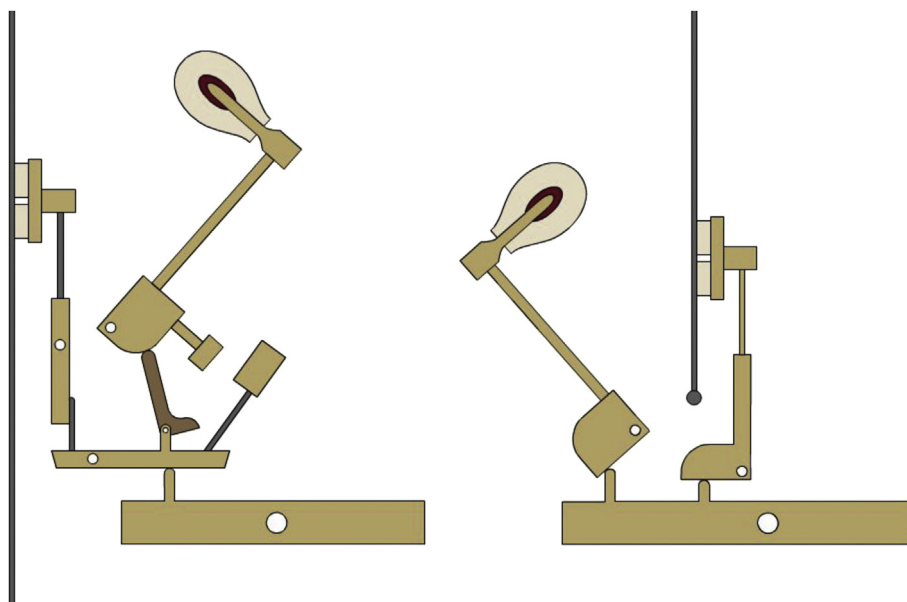


Fig. 7. Static depictions of original and transfer piano mechanisms. Note differences in aspects such as number of entities, shape/structure of entities, orientation, and overall arrangement.

form of successively delivered pairs of event units. With entity repetitions, this meant that each entity was exposed a total of eight times across the entire presentation. The presentation duration was the same for both contiguous and non-contiguous versions. For the control (comprehensive) condition, the animation was presented a total of nine times in succession (an extra presentation above the eight required to match the other versions being added in order to balance total pause time between presentations across the three conditions). As a result, the total time of exposure to the movement of each mechanism component was identical across conditions. After having viewed their respective versions, participants performed the local kinematics task then generated an exhaustive written account the piano mechanism's operation. The session ended with the transfer task. After completion of the experimental tasks, a check requiring participants to identify components established that they could all discriminate between them.

3. Results

3.1. Learning outcomes

Learning outcomes are presented in Table 1 (with results as percentages in italics). Scores were analyzed using ANOVAs (mental model quality, local kinematics, transfer) and regression (transfer).

3.1.1. Mental model quality

An ANOVA with animation design as the between subjects factor and mental model quality scores as the dependent measure showed a significant difference amongst the groups, $F(2,57) = 5.81$, $p = 0.005$ $\eta p^2 = 0.17$. This analysis indicates that learners in the contiguous condition built higher quality mental models than learners in the other conditions. Univariate comparisons revealed that participants in the contiguous condition had significantly higher scores than did those in the non-contiguous and control conditions, $F(1,57) = 10.40$, $p = 0.002$, $d = 1.04$; $F(1, 57) = 6.61$, $p = 0.012$, $d = 0.91$. Further, scores were not significantly different between the non-contiguous and the control conditions, $F(1, 57) = 0.42$, $p = 0.51$, $d = 0.18$.

3.1.2. Local kinematics

An ANOVA with animation design as the between subjects factor and local kinematics scores as the dependent measure revealed no significant effect of condition, $F(2,57) = 1.26$, $p = 0.29$, $\eta p^2 = 0.042$. Univariate comparison revealed there was also no significant difference between the contiguous and non-contiguous conditions, $F(1, 57) = 2.50$, $p = 0.11$, $d = 0.49$.

3.1.3. Transfer

The observed pattern of scores for participants in the contiguous, non-contiguous and control conditions was in the expected direction. Hypothesis 1A postulated a positive link between the

quality of the mental model developed from studying the original piano mechanism animation and the ability to transfer the knowledge acquired to a different piano mechanism presented in a static diagram format. A simple regression involving mental model quality scores and kinematics scores for the transfer task diagram revealed a significant relationship between these two scores, *multiple* $R^2 = 0.14$, $F(1,58) = 9.60$, $p = 0.003$, $Beta = 0.38$.

However, an ANOVA with animation design as the between subjects factor and transfer score as the dependent variable indicated that the difference in scores was not significant, $F(2, 57) = 1.85$, $p = 0.16$. Univariate comparisons revealed a marginally significant difference between the contiguous and the non-contiguous conditions, $F(1,57) = 3.53$, $p = 0.06$, $d = 0.61$; and also between the contiguous condition and both non-contiguous and control conditions, $F(1, 57) = 3.52$, $p = 0.072$, $d = 0.51$.

3.2. Eye tracking

Table 2 presents the mean fixation durations, counts, and duration/count ratios for the contiguous, non-contiguous and control conditions.

There was a high and significant negative correlation between mean fixation duration and count, $r(54) = -0.81$, $p < 0.0001$. As noted earlier, longer fixation durations and lower fixation counts have been interpreted as indicating deeper processing which, in the context of the present study, are likely to reflect the intense, focused processing required to understand relationships. Conversely, shorter durations and higher counts likely reflect more exploratory, distributed processing (e.g., scanning and searching). The ratio of mean fixation duration (milliseconds) to fixation count was therefore used as a relational index to gauge the relative emphasis on relational versus exploratory processing.

A one factor ANOVA with animation design as the between subjects factor and relational index as the dependent variable revealed that results for the contiguous, non-contiguous and control groups were significantly different, $F(2, 51) = 5.41$, $p = 0.007$, $\eta p^2 = 0.17$. This suggests a clear tendency for those in the contiguous condition to engage in more relational processing whereas the processing of those in the non-contiguous and control groups tended to be more exploratory.

Table 2
Mean fixation durations, counts and duration/count ratios in the seven AOs (by design condition).

Measures: Means (SD)	Condition		
	Contiguous	Non-contiguous	Control
Fixation duration (milliseconds)	480 (130)	390 (80)	410 (60)
Fixation count	461 (106)	539 (94)	541 (90)
Duration/count ^a	1.12 (0.51)	0.77 (0.24)	0.79 (0.27)

^a Relational Index.

Table 1
Mean scores (absolute and %) for different animation design conditions.

Performance Scores: Mean absolute (SD) and % (SD)	Condition		
	Contiguous	Non-contiguous	Control
Mental model quality/15	6.47 (1.67)	4.12 (2.73)	4.60 (2.38)
%	43.16 (11.15)	27.50 (18.22)	30.67 (15.88)
Local kinematics/50	24.60 (7.63)	21.22 (5.95)	22.67 (6.54)
%	49.20 (15.26)	42.45 (11.90)	45.35 (13.09)
Transfer (kinematics)/32	17.90 (4.39)	15.02 (4.95)	15.92 (5.13)
%	55.94 (13.73)	46.95 (15.47)	49.76 (16.04)
Overall performance %	49.43 (10.88)	38.97 (11.49)	41.93 (12.60)

Direct examination of individual eye tracking videos from participants in the different conditions supported this interpretation by revealing three clear and distinctive patterns of inspection. Participants in the control group tended to make many mostly short and widely distributed fixations by which most of the mechanism's six constituent entities were visited once or twice per operational stage. They also made occasional longer fixations. This pattern was essentially the same as that observed in previous studies using this comprehensive animation (e.g., Boucheix & Lowe, 2010; Boucheix et al., 2013). Those in the non-contiguous group exhibited a very different pattern, with a clear tendency to alternate more frequently between the entities of each displayed pair and to make multiple fixations within the boundaries of individual entities. These fixations were mostly of relatively short duration. The patterns from the contiguous group were different again and especially notable for prolonged fixations on the junction at which the two entities comprising a relation set interacted during operation of the mechanism. Although there were also some shorter fixations within and between the different entities, these were very much in the minority.

4. Discussion

In the present study, we examined the effect on learning of an alternative and principled way of designing educational animations that we have termed a *composition approach*. Our main aim in this first investigation of APM-based animation design was to test the general feasibility of such an approach with regard to complex mechanical subject matter and domain novices. The goal of the study reported here was relatively modest because it addressed only bottom-up aspects of the APM (particularly, alleviation of the substantial problems that learners have in decomposing conventional comprehensive animations). Further, we did not attempt to maximize the potential effectiveness of compositional design through more sophisticated forms of sequencing.

In general, the results of this study were consistent with our expectations. [Hypothesis 1](#), was supported, with the explanations of the piano mechanism's operation given by those who studied the compositional animation (contiguous condition) indicating they developed significantly higher quality mental models for this device than did those in the other two groups (non-contiguous and comprehensive conditions). Supplying learners with pre-decomposed raw material (parts of the whole) in this way was more effective than using a conventional design that presents them with the subject matter in its entirety. However, for this novel approach to be successful, it is not sufficient just to reduce the amount of information that learners are presented per unit time. The fact that those in the non-contiguous group developed inferior mental models (similar in quality to those in the comprehensive group) suggests that the effectiveness of the compositional animation cannot be explained in terms of reduced processing load alone. Although the subsets of information provided to both contiguous and non-contiguous groups consisted of pairs of event units (presented at the same rate), there were key differences between the pairs with regard to constitution and sequencing. The contiguous animations used relation sets consisting of adjacent pairs of event units that portrayed direct functional interactions. Further, presentation of these relation sets was sequenced in a manner that allowed them to be interlinked via a common event unit and be progressively compiled along the course of the mechanism's causal chains. These aspects are highly consistent with the processes posited by the APM (see [Fig. 1](#)) for the relational part-whole processing of local segments into broader structures (Phase 2) and their subsequent connection to bridge across 'islands

of activity' (Phase 3). In contrast, the pairs used in the non-contiguous animation were non-adjacent – they were therefore not localized and had no direct functional interaction. In addition, the quasi-random presentation order militated against their part-whole connection into higher order relational structures.

Results for the transfer test did not support [Hypothesis 1A](#). Specifically, those who studied the compositional animation were not significantly better at applying their mental models of how the original piano works to the novel mechanism (although the regression analysis did indicate that better transfer was generally associated with superior mental models). A possible explanation for this lack of transfer benefit for those in the compositional animation group lies in the specific characteristics of the novel piano mechanism used for this assessment. Although the original and transfer mechanisms have various notable differences, particularly with respect to configuration ([Fig. 7](#)), the transfer mechanism is actually simpler in terms of its functionality. It has a smaller number of functional components, fewer possibilities for their movement, and less mediation of movements by intervening entities. This makes it easier to infer how the individual components may move. In hindsight, it would probably have been better to use a more complex novel piano mechanism for this transfer task.

[Hypothesis 2](#) was supported in that there was no significant differences in local kinematics scores across conditions. This result is consistent with what would be predicted from the APM in that this measure deals with the behavior of individual entities in isolation, not specifically with the relationships between them. Although it would be relatively easy for participants in any of the conditions to extract such isolated fragments of information from all animation versions, extraction of required information about how they are related is much less straightforward.

The prediction of [Hypothesis 3](#) that the three animation designs would engender differences in visual processing (as indicated by fixation durations and frequencies) was supported by the eye tracking results. The compositional animation was designed not only to relieve learners of the decomposition burden (APM Phase 1) but also to provide conditions likely to foster the types of relational processing that are essential for linking low level dynamic information (individual event units) into high level knowledge structures. The relational indices for the three designs suggest that the compositional animation was indeed more likely to foster the hierarchical part-whole interlinking assumed to occur during mental model building. Qualitative data from the eye tracking videos were consistent with the interpretation that those viewing the compositional animation devoted more perceptual (and probably cognitive) resources to establishing the types of linkages posited to be formed in APM Phase 2 and 3 processing. The extended attention on the locus of interaction between event units suggests that those in the contiguous condition were engaged in efforts to characterize their dynamic relationship. In contrast, the patterns exhibited by those in the control and non-contiguous conditions are more consistent with search for the *presence* of relationships rather than efforts to establish the *nature* of such relationships.

Despite its limited scope, results from this initial study suggest that alternatives to the prevailing conventional approaches to animation design are worth pursuing. As observed in a recent meta-analysis: "It may therefore be that 'well-designed' animations are self-sufficient to draw learners' attention to the right place at the right time." ([Berney & Bétrancourt, 2016, p160](#)). However, the limitations of this investigation should be addressed by future work in this area, particularly regarding how to further improve mental model quality, the extent to which these results may or may not be generalizable to other types of subject matter, and its applicability to learners with different levels of background knowledge/

expertise. A better understanding of the reasons for the eye tracking patterns observed would also be helpful. In addition, as already noted, the issue of transfer (as an operational indicator of mental model quality) needs further investigation with respect to what are the most suitable forms of transfer task.

Although designed on the basis of the APM, the composition approach could also be framed in terms of theoretical and empirical work on sequencing instruction, particularly regarding part-whole sequencing. The form of sequencing we implemented in this study of compositional design was somewhat rudimentary and placed considerable reliance on the learner being able to build mental models with relatively little assistance. Its presentation of relation sets was via a simple A,B,C... approach in which there was no explicit progressive accumulation in the dynamic structures over time. While it is most encouraging that participants in the compositional animation group were nevertheless able to achieve mental model quality scores that were around one and a half times those in the other groups, their absolute scores were still rather low (below 50%). In order to further increase such scores, it is likely that the design approach needs to be refined and elaborated to provide even greater support for beneficial relational processing. One possibility would be to use a 'snowballing' type of sequencing (A, A+B, A+B+C, ...) which provides a more structured pathway for building complex hierarchical knowledge representations (Kester et al., 2004a, 2004b, 2005; Van Merriënboer & Kester, 2014; Van Merriënboer et al., 2003). Modifying the compositional approach to include this more sophisticated form of sequencing would be perfectly consistent with the iterative, cumulative processing posited by the APM (Lowe & Boucheix, 2008). However, other sequencing possibilities that could be investigated (e.g., whole-part) (De Jong & Lazonder, 2014; Van Merriënboer et al., 2003) may be less suitable because of the potential problems such as decomposition challenges, the possibility of overwhelming, etc. that can occur with complex animations. Nevertheless, there may still be benefits if learners view the dynamic subject matter as a whole (as indicated by exit interviews with our participants), provided it is done after presentation by parts.

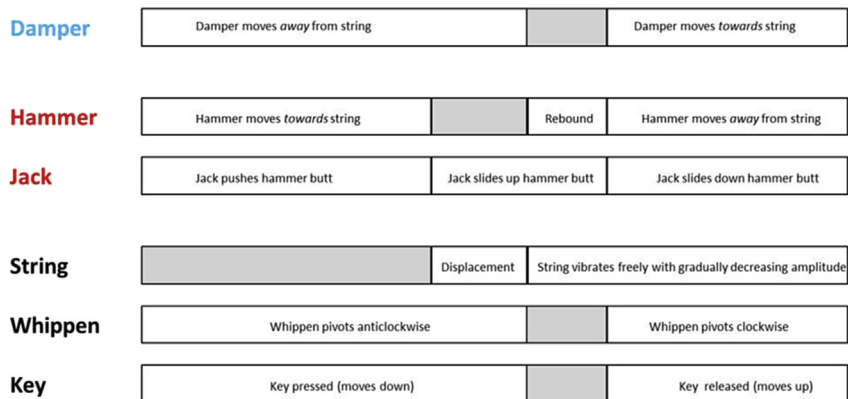
The animations used in the present investigation depicted a complex and unfamiliar mechanism. It is possible that, although

effective for mechanical subject matter such as this, compositional animation designs may not be well suited to other classes of content. For example, the human information processing limitations that are problematic with animations of mechanical systems and the like may not pertain when the subject matter depicts human movements because of the role played by the mirror neuron system (Van Gog, Paas, Marcus, Ayres, & Sweller, 2009). Some studies have already shown that simpler forms of part-whole treatment, such as segmentation along the animation's time course, have positive effects on learning when the subject matter depicted consists of complex manual procedures such as knot tying. (Boucheix & Forestier, in press; Wong et al., 2012). Whether or not the additional design effort involved in producing a compositional animation (rather than using a simpler segmentation) is warranted for animations depicting human movements should be investigated by future research to indicate the generalizability of the results reported here.

As noted, the instantiation of the compositional approach investigated in the present study focused on aspects of animation processing that the APM characterizes as largely bottom-up in nature. It did not explicitly target more top-down contributions to processing. This limitation should be addressed in future research because the research literature on learning from animations has shown that prior knowledge and expertise can have a major influence on how effectively animations are processed. (Höffler & Leutner, 2007; Lowe, 1999; Khacharem et al., 2012; Spanjers et al., 2011). The APM incorporates this top-down aspect of processing, particularly in Phases 4 and 5. Our participants all lacked knowledge and expertise with regard to the subject matter, a situation commonly encountered when animations are used in education (especially when complex, unfamiliar ideas are being introduced). Subsequent studies could investigate the effectiveness of compositional animations for participants with different levels of expertise in the domain or possibilities for elaborating the design of such animations in order to compensate for a lack of prior knowledge.

Appendix A

Event Unit* Analysis – Piano Mechanism



Time

*  = 'null' event unit

Appendix B

Scoring guide for the verbal test of mental model quality.

Stage 1: Striking.

- 1 When the key is pressed (by the pianist), it moves the key-sticker at the end of the key upwards.
- 2 The key-sticker raises the whippen that makes a rocking motion as a result.
- 3 The raising of the whippen operates the jack.
- 4 The upward moving jack pushes up the hammer butt.
- 5 The hammer-butt pivots on its axle.
- 6 The pivoting of the hammer-butt moves the hammer toward the string.
- 7 The hammer strikes the string to produce the note.
- 8 At the same time, the rocking motion of the whippen pushes the damper to lift it off the string.
- 9 The release of the damper liberates the string to sound freely when struck by the hammer.

Stage 2: Recovering.

- 10 The hammer instantly rebounds backwards once it has struck the string.
- 11 The balance hammer is caught and blocked by the back-check in order to limit the hammer's backward travel. The system stays in this position as long as the key remains depressed.

Stage 3: Resetting.

- 12 When the key is released, the whippen drops.
- 13 The back check releases the balance hammer.
- 14 The jack moves downward under the butt and the hammer returns to its initial position.
- 15 At the same time, the damper returns to the string

References

- Berney, S., & Bétrancourt, M. (2016). Does animation enhance learning? A meta-analysis. *Computers & Education*, *101*, 150–167.
- Boucheix, J.-M. (2008). Young learners' control of technical animations. In R. K. Lowe, & W. Schnotz (Eds.), *Learning with animation: Research implications for design* (pp. 208–234). Cambridge, UK: Cambridge University Press.
- Boucheix, J.-M., & Lowe, R. K. (2010). An eye tracking comparison of external pointing cues and internal continuous cues in learning with complex animations. *Learning and Instruction*, *20*, 123–135.
- Boucheix, J.-M., Lowe, R. K., & Bugaiska, A. (2015). Age differences in learning from instructional animations. *Applied Cognitive Psychology*. <http://dx.doi.org/10.1002/acp.3131>.
- Boucheix, J.-M., Lowe, R. K., Putri, D. K., & Groff, J. (2013). Cueing animations: Dynamic signaling aids information extraction and comprehension. *Learning and Instruction*, *25*, 71–84. <http://dx.doi.org/10.1016/j.learninstruc.2012.11.005>.
- Clarke, T., Ayres, P., & Sweller, J. (2005). The impact of sequencing and prior knowledge on learning mathematics through spreadsheet applications. *Educational Technology, Research and Development*, *53*, 15–24.
- De Jong, A. J. M., & Lazonder, J. (2014). Learning with scientific simulation. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 504–514). New-York: Cambridge University Press.
- De Koning, B. B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2007). Attention cueing as a means to enhance learning from an animation. *Applied Cognitive Psychology*, *21*, 731–746.
- De Koning, B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2010). Improved effectiveness of cueing by self-explanations when learning from a complex animation. *Applied Cognitive Psychology*, *25*, 183–194.
- Fischer, S., Lowe, R. K., & Schwan, S. (2008). Effects of presentation speed of a dynamic visualization on the understanding of a mechanical system. *Applied Cognitive Psychology*, *22*, 1126–1141.
- Godberg, J., & Kotval, X. (1999). Computer interface evaluation using eye movements: Methods and constructs. *International Journal of Industrial Ergonomics*, *24*, 631–645.
- Höfler, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction*, *17*, 722–738.
- Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & van de Weijer, J. (2011). *Eye tracking: A comprehensive guide to methods and measures*. London: Oxford University Press.
- Hyönä, J. (2010). The use of eye movements in multimedia learning. *Learning and Instruction*, *20*, 172–176.
- Kester, L., Kirschner, P. A., & Van Merriënboer, J. J. G. (2004a). Information presentation and troubleshooting in electrical circuits. *International Journal of Science Education*, *26*, 239–256.
- Kester, L., Kirschner, P. A., & Van Merriënboer, J. J. G. (2004b). Timing of information presentation in learning statistics. *Instructional Science*, *32*, 233–252.
- Kester, L., Kirschner, P. A., & Van Merriënboer, J. J. G. (2005). The management of cognitive load during complex cognitive skill acquisition by means of computer simulated problem solving. *British Journal of Educational Psychology*, *75*, 1–16.
- Khacharem, A., Spanjers, I., Zoudji, B., Kalyuga, S., & Ripoll, H. (2012). Using segmentation to support the learning from animated soccer scenes: An effect of prior knowledge. *Psychology of Sport and Exercise*, *14*, 154–160.
- Kombartzky, U., Ploetzner, R., Schlag, S., & Metz, B. (2010). Developing and evaluating a strategy for learning from animation. *Learning and Instruction*, *20*, 424–433.
- Limniou, M., & Whitehead, C. (2010). Online general pre-laboratory training course for facilitating first year chemical laboratory use. *Cypriot Journal of Educational Sciences*, *5*, 39–55.
- Lowe, R. K. (1999). Extracting information from an animation during complex visual learning. *European Journal of Psychology of Education*, *14*, 225–244.
- Lowe, R. K. (2003). Animation and learning: Selective processing of information in dynamic graphics. *Learning and Instruction*, *13*, 157–176.
- Lowe, R. K. (2004). Interrogation of a dynamic visualization during learning. *Learning and Instruction*, *14*, 257–274.
- Lowe, R. K. (2008). Learning from animation: Where to look, when to look. In R. K. Lowe, & W. Schnotz (Eds.), *Learning with animation: Research implications for design* (pp. 49–68). New York: Cambridge University Press.
- Lowe, R. K. (2014). Dynamic visualizations: A two-edged sword? In W. Huang (Ed.), *Handbook of human centric visualization* (pp. 266–281). New York: Springer.
- Lowe, R. K., & Boucheix, J.-M. (2008). Learning from animated diagrams: How are mental models built? In G. Stapleton, J. Howse, & J. Lee (Eds.), *Diagrammatic representation and inference* (pp. 266–281). Berlin: Springer.
- Lowe, R. K., & Boucheix, J.-M. (2011). Cueing complex animation: Does direction of attention foster learning processes? *Learning and Instruction*, *21*, 650–663.
- Lowe, R. K., & Boucheix, J.-M. (2012). Dynamic diagrams: A composition alternative. In P. Cox, B. Plimmer, & P. Rogers (Eds.), *Diagrammatic representation and inference* (pp. 233–240). Berlin: Springer.
- Lowe R.K., Designing static and animated diagrams for modern learning materials. To appear in the *Gower Handbook of Information Design* in press, Gower, London.
- Lowe, R. K., & Schnotz, W. (2008). *Learning with animation: Research implications for design*. New York: Cambridge University Press.
- Lowe, R. K., & Schnotz, W. (2014). Animation principles in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (2d Ed., pp. 513–546). New York: Cambridge University Press.
- Mason, L., Lowe, R. K., & Tornatora, M. C. (2013). Self-generated drawings for supporting comprehension of a complex animation. *Contemporary Educational Psychology*, *38*, 211–224.
- Mayer, R. E., Mathias, A., & Wetzell, K. (2002). Fostering understanding of multimedia messages through pre-training: Evidence for a two-stage theory of mental model construction. *Journal of Experimental Psychology: Applied*, *8*, 147–154.
- Mayer, R. E., & Moreno, R. (2003). Nine ways to reduce cognitive load in multimedia learning. *Educational Psychologist*, *38*, 43–52.
- Mayer, R. E., & Pilegard, S. (2014). The pre-training principle. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 104–148). New-York: Cambridge University Press.
- Meyer, K., Rasch, T., & Schnotz, W. (2009). Effects of animation's speed of presentation on perceptual processing and learning. *Learning and Instruction*, *20*, 136–145.
- Musallam, R. (2010). *The effects of using screencasting as a multimedia pre-training tool to manage the intrinsic cognitive load of chemical equilibrium instruction for advanced high school chemistry students*. Unpublished doctoral dissertation. United States of America: the University of San Francisco.
- Naylor, J. C., & Briggs, G. E. (1963). Effects of task complexity and task organization on the relative efficiency of part and whole training methods. *Journal of Experimental Psychology*, *65*, 217–224.
- Ploetzner, R., & Lowe, R. K. (2012). A systematic characterization of expository animations. *Computers in Human Behavior*, *28*, 781–794.
- Ploetzner, R., & Lowe, R. K. (2014). Simultaneously presented animations facilitate the learning of higher-order relationships. *Computers in Human Behavior*, *34*, 12–22.
- Ploetzner, R., & Schlag, S. (2013). Strategic learning from expository animations: Short- and mid-term effects. *Computers & Education*, *69*, 159–168.
- Pollock, E., Chandler, P., & Sweller, J. (2002). Assimilating complex information. *Learning and Instruction*, *12*, 61–86.
- Rebetz, C., & Bétrancourt, M. (2009). Simultaneous static or animated graphics in the construction of a dynamic mental model. In *Proceedings of the 13th EARLI biennial conference on research on learning and instruction*, Aug. 28-Sept. 1,

- Amsterdam (NL).
- Scheiter, K. (2014). The learner control principle in multimedia learning. In R. E. Mayer (Ed.), *The cambridge handbook of multimedia learning* (pp. 487–512). New-York: Cambridge University Press.
- Schnotz, W., & Lowe, R. K. (2008). A unified view of learning from animated and static graphics. In R. K. Lowe, & W. Schnotz (Eds.), *Learning with animation: Research implications for design* (pp. 304–356). New York: Cambridge University Press.
- Spanjers, I. A. E., Van Gog, T., & Van Merriënboer, J. J. G. (2010). A theoretical analysis of how segmentation of dynamic visualizations optimizes students' learning. *Educational Psychology Review*, 22, 411–423. <http://dx.doi.org/10.1007/s10648-010-9135-6>.
- Spanjers, I. A. E., Wouters, P., Van Gog, T., & van Merriënboer, J. J. G. (2011). An expertise reversal effect of segmentation in learning from animated worked out examples. *Computers in Human Behavior*, 27, 46–52.
- Van Gog, T., Paas, F., Marcus, N., Ayres, P., & Sweller, J. (2009). The mirror neuron system and observational learning: Implications for the effectiveness of dynamic visualizations'. *Educational Psychology Review*, 21(1), 21–30.
- Van Merriënboer, J. J. G. (1997). *Training complex cognitive skills: A four-component instructional design model for technical training*. Englewood Cliffs, NJ: Educational Technology Publications.
- Van Merriënboer, J. J. G., & Kester, L. (2014). The four-component instructional design model: Multimedia principles in environments for complex learning. In R. E. Mayer (Ed.), *The cambridge handbook of multimedia learning* (pp. 104–148). New-York: Cambridge University Press.
- Van Merriënboer, J. J. G., & Kirschner, P. A. (2013). *Ten steps to complex learning* (2nd Rev.Ed.). New York: Routledge.
- Van Merriënboer, J. J. G., Kirschner, P. A., & Kester, L. (2003). Taking the load of a learners' mind: Instructional design for complex learning. *Educational Psychologist*, 38, 5–13.
- White, B. Y., & Frederiksen, J. R. (1990). Causal model progressions as a foundation for intelligent learning environments. *Artificial Intelligence*, 42, 99–157.
- Wong, A., Leahy, W., Marcus, N., & Sweller, J. (2012). Cognitive load theory, the transient information effect and e-learning. *Learning and Instruction*, 22, 449–457.