Effects of Presentation Speed of a Dynamic Visualization on the Understanding of a Mechanical System

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Abstract

In an experimental study, the role of temporal variation of a realistic animation was examined. The animation of a complex mechanical system, a pendulum clock, was presented in a between subject design at normal or fast speed. Presentation speed was found to affect distribution of attention and understanding of the functionality of the clockwork mechanism. Verbal reports in the fast condition contained more statements on the weight, which is a central part of the clocks' mechanism. When giving a written description of the clock, subjects who saw the fast presentation produced more correct and less false concepts about the key components of the clockwork. For complex subject matter, it seems possible that speed could be used strategically by instructional designers to raise the perceptual salience of thematically relevant aspects of the display, by means of faster or slower presentation speeds.

Instructional Uses of Temporal Manipulations

This paper focuses upon temporal properties of a dynamic display and explores the effect of presentation speed on the processing of information in an animated depiction of a complex mechanical device (a pendulum clock).

Dynamic visualizations of various types are increasingly used in educational resources for presenting subject matter that involves change over time. Intuitively, these representations appear well suited to helping learners understand change phenomena because they provide explicit depiction of the referent situation's dynamics instead of requiring the learner to reconstruct the dynamics via mental animation from static graphics. Nevertheless, dynamic visualizations have not proven to be a universal panacea for the challenges involved in comprehending change phenomena. Merely *providing* change-related information as an analogue dynamic representation does not guarantee that learners will necessarily be able to extract its key aspects (Lowe, 1999, 2003, 2004). Particularly when the subject matter is complex and unfamiliar, learners appear to respond to the consequent high level of information processing demands by selectively attending to aspects of the display that have greatest perceptual salience relative to the rest of the display. Unfortunately, such aspects are not necessarily those of most relevance to the central theme of the presentation. Both the visuospatial characteristics of a dynamic visualisation (such as the size, shape, colour, and arrangement of its component entities) and its temporal properties (such as playing speed, direction, and continuity) have the potential to affect the relative perceptual salience of displayed information.

Accordingly, research into learning from dynamic visualizations has produced mixed findings. For example, while Schwan and Riempp (2004), found that user-controllable videos facilitated the learning of knot-tying tasks, no corresponding facilitation effect was found in studies by Lowe (2003) of learning meteorological prediction skills from a user-controllable weather map animation. A likely reason for the mixed results is that such studies differed in a number of key respects. One important way they differ is in the type of content that is presented, which can range from concrete subject matter such as mechanical devices to highly abstract material such as visualizations of mathematical algorithms. In addition to these content differences, there are also differences in how literally the specific content is depicted. The issue here is one of the extent to which the visuospatial and temporal properties of the depiction resemble those of the real life referent. In terms of visuospatial properties, the *appearance* of the depicted content can be presented with varying degrees of realism, ranging from extremely realistic portrayals (as with films, videos, and realistically rendered animations) through to highly schematic renditions that embody extensive manipulation of the referent (such as animated diagrams). With temporal properties, the *behaviour* of the depicted content can also be presented with varying degrees of realism. At one extreme, the dynamic visualization has a strict moment-to-moment correspondence with the referent situation; at the other, temporal characteristics such as presentation speed and order have been extensively manipulated.

Strict maintenance of the actual temporal properties of a referent system in its depiction can pose processing challenges for learners. For example, because animation is a fleeting form of representation (Ainsworth & Van Labeke, 2004), there is potential for learners to miss key information because it is displayed only very briefly or to lose information because it is 'overwritten' in working memory by what is presented subsequently (Lowe, 1999). Such failures to extract or retain key information are likely to prejudice the individual's capacity to construct a high quality mental model of the referent situation and so have negative effects on learning. The current preoccupation with *behavioural realism* (Lowe, in press) in the design of educational animations should perhaps be challenged because of potential conflicts between a realistic presentation regime and constraints on human processing of temporal information. Rather than privileging the temporal properties of the subject matter in its depiction, it may be that dynamic visualizations would be more effective if these properties were manipulated in order to facilitate their processing by learners.

Extensive manipulation of the visuospatial characteristics of static graphics has a long history within educational materials. It is well accepted as a way of making those representations more effective for learners. For example, it is standard practice in explanatory diagrams to omit material, simplify entities, re-organise structure, and visually emphasise key aspects. With today's technology, instructional designers now have the option to incorporate analogous manipulations of temporal properties in dynamic visualizations (Schwan, Garsoffky, & Hesse, 2000; Schwan & Garsoffky, 2004). Precedents already established in the film and television industry may help point towards some possibilities, e.g. the use of time-lapse and slow-motion in movies, commercials and sports reports (Visch & Tan, in press). Despite the accepted use of altered speed in films and television for affective and aesthetic purposes, systematic empirical investigation of its effects on learning-related perceptual and cognitive processing is lacking. One of the few studies concerning presentation speed was carried out by Newtson and Rindner (1979) who found that showing a filmed problem solving sequence in slow-motion or time-lapse had effects on segmentation, memory, and estimates of future performance.

Changing the presentation speed of an animation could have a number of possible perceptual and cognitive consequences. One possibility is that the amount of information that can be processed is affected. For example, a slower presentation may allow viewers to deal with more of the available information because the speed is better matched to the limits of their available processing capacity. Alternatively, changing the speed may have a much more fundamental effect at the level of the relative perceptual salience of the different entities portrayed. For example, at a faster playing speed, an entity that was previously low in perceptual salience because it did not contrast sufficiently with its surroundings could become more noticeable.

Mechanical Pendulum Clocks as Complex Dynamic Phenomena

Complex dynamic phenomena can be conceptualised as a hierarchy of event chains that exist at several different temporal scales. On each level, the event chains may run independently. They can be triggered by event chains on another level and progress linearly, but they can also be cyclic, depending fully or partly on their own previous states and events. The levels may be interrelated by cross-level constraints. The animation of a mechanical pendulum clock used in this study portrays such a complex dynamic device which is characterized by a cyclic system with a hierarchically-organized event structure embodied in three main sub-systems: (i) a drive mechanism (ii) a transmission system, and (iii) an analogue time display. Each of these sub-systems consists of a number of interconnected components that vary in their visuospatial and temporal properties. Table 1 summarises key information about these sub-systems.

A precondition for building a satisfactory mental model of a complex dynamic phenomenon from an animation is that the behaviour of its key functional components is extracted from the presentation. For a pendulum clock these key components are the pendulum, escapement and, most fundamentally the weight, which as the drive mechanism comprise the central sub-system of the clock. When the phenomenon involves many and varied entities as well as a wide range of dynamic changes, there will be considerable competition for the viewer's limited attentional capacities. Particular aspects of the display will be noticed to the neglect of others, according to their specific visuospatial and temporal properties relative to the broader display context. For example, large, fast-moving entities near the centre of the display are more likely to attract attention than small, slow-moving entities near its periphery. Changing the overall speed of an animation potentially alters the relative perceptibility of particular aspects of the display due to the dynamic contrast effect (Lowe, 2005).

In the animation used for the present experiment, clock components were rendered at the same level of brightness in a limited range of 'natural' colours. This treatment allowed the components to be clearly distinguished from one another while avoiding colour cueing of some aspects over others. Inspection of Table 1 and Figure 1 shows that there are considerable differences in the visuospatial and temporal properties of the clock system's various components. As a consequence, it is likely that some aspects of its normal operation (i.e., when running at a realistic speed) would be more intrinsically perceptible than others. For example, the pendulum is large, distinctively-shaped, and its movement occupies much of the visual field whereas many of the gears are small, similarly-shaped, and their movements occupy little of the visual field.

In order to understand the clock's operation from the animation, it is necessary to build a high quality dynamic mental model of the device. The effectiveness of this model construction activity is likely to depend on both bottom-up and top-down processing of the presented information. Bottom-up aspects processing will largely be influenced by perceptual attributes of the animated display, while background knowledge about mechanical pendulum clocks and the nature of the task will guide top-down processing. As discussed above, the components shown in the clock animation vary along a number of perceptually-relevant dimensions with respect to their visuospatial and temporal properties. However, the way in which attention is directed amongst these components will be only partly determined by their relative percepti-

Table 1: Sub-systems.

Sub-System	Components	Function	Visuospatial Character	Temporal Character
Drive mechanism	Weight	Energy source	Small, bottom-centre, cylinder plus vertically oriented chain	Very slow, linear downward movement over a large distance
	Pendulum	Pulse generator	Large, on the right side, vertically oriented	Fast oscillation ranging over a medium size area
	Escapement	Energy release controller	Medium sized, most right gear with specially shaped teeth and anchor	Fast seesaw movement of the anchor in a small region on top of the escape wheel
Transmission System	Gears	Energy distribution and transmission	Small and medium sized gears, placed central, with highly symmetric shape	Fast, medium and slow rotations of different gears in both directions
	Arbors	Mounting and connecting gears	Small, in the center, with horizontal orientation	Fast, medium and slow spinning causes textural change
Analogue Display	Hour hand	Display hours	Medium sized, centered on the left,	Very slowly circling over a medium sized area
	Minute hand	Display minutes	Large, centered on the left	Slowly circling over large area
	Second hand	Display seconds	Small, at the upper left	Fast circling over small area

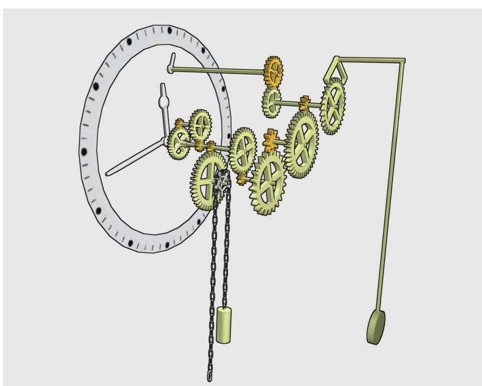

Figure 1: Frame from pendulum clock animation.

bility. Direction of attention will also be shaped by what the individual viewer already knows about clocks in general and mechanical pendulum clocks in particular. For example, unless the viewer has specific expertise about clock mechanisms, s/he will know far more about the visible aspects of the clock (the hands, weight, and pendulum) than the hidden parts of its mechanism. Further, if the task is to understand the mechanism, attention is likely to be preferentially directed to those components that are known from everyday experience to be crucial to its operation (such as the weight and the pendulum).

In this study, animations showed the clock operating either at normal speed or greatly speeded up. It seems reasonable to expect that bottom-up and top-down aspects of processing would interact, with the effect of changes in perceptual salience of clock components due to speed differences being modulated by background knowledge of component functionality. This leads to a number of hypotheses:

Hypotheses

On the level of attentional processes, it was expected that different presentation speeds would affect distribution of attention and lead to different attentional profiles. Indicators for attention should be found in verbal reports and pointing behaviour during animation perception. On the level of comprehension, improved mental model building and understanding was expected, if a changed presentation speed increases attention to thematically relevant components. For the pendulum clock this should be achieved by increasing attention to the key components of the drive mechanism (i.e. pendulum, escapement and particularly the weight).

Method

Participants

Thirty-six students from the University of Tübingen were paid for their participation. Four were excluded from the analysis: two already had an exceptionally high level of expertise about clocks, one demonstrated a lack of motivation, and one misinterpreted the thinking aloud instruction as meaning free association. For the remaining 32 subjects the average age was 23.8 years (24 female and 8 male). In each condition there were 16 subjects, 11 female and 5 male in the normal, and 13 female and 3 male in the fast condition.

Apparatus

Animations were shown full screen on a multimedia PC with 3 GHz connected to a 19” TFT Display with 60 Hz and 479 mm screen diagonal at a resolution of 1280 x 1024 pixel.

Stimulus Material

The clockwork animations were modeled and rendered using Blender[1] and the Python scripting language. For each condition, a separate animation was rendered, one with the animation's speed set to real time and the other one set to 210 times normal speed. This factor was chosen to minimize temporal aliasing effects through the sampling rate determined by the animation frame rate of 25 Hz. Adjustments were made in the display of the fast animation to ensure that for the different angular velocities of the gears, the motion impression was appropriate and not disturbed by a reverse rotation effect. This effect, also called the wagon wheel illusion, is not restricted to media presentations, but also occurs in real life and under constant light conditions (Purves, Paydarfar, & Andrews, 1996; Kline, Holcombe, & Eagleman, 2004).

The final animation[2] shown to the subjects started with a front-on viewpoint of the clock face. The clock was not operating at this point and the viewpoint moved on a circular path around the center of the clockwork, providing a 20-second introduction to the overall structure of the mechanism. The viewpoint then arrived at a perspective showing the clockwork at 140 degrees from a rear-side view as shown in Figure 1. The viewpoint and the length of the arbors was chosen to minimize occlusions and clearly display each gear's movement. The final view of this introductory presentation was then faded out and the clockwork in the same position, but in motion rather than static, was faded in. The animation continued for 5 minutes and was then repeated, being faded out and again in immediately. This repetition was necessary, because the length of the weight's chain was chosen according to the viewpoint distance. A longer chain would have resulted in the weight being out of viewing range the most time, and a more distant viewpoint would have lost details of the clockwork. By repeating the animation sequence, the time that subjects had to examine the animation was doubled, leading a total length of 10 minutes 20 seconds for the animation. Pilot testing indicated this period was sufficient to understand the clock.

Procedure

Subjects were first given a short introduction explaining that the aim of the study was to investigate the appropriateness of animations for understanding mechanical devices. Subjects were asked to verbalize their thoughts while being videoed from behind to capture pointing behavior. After an initial questionnaire for prior knowledge, a warm-up task in which participants were asked to describe Renoir's painting 'Moulin Galette' was used to accustom participants to thinking aloud and being video recorded. The animation was then shown, with participants set the task of trying to understand how the clock functions.

After the animation, the terms 'Anker' (anchor) and 'Hemmungsrad' (escape wheel) were introduced by naming them while pointing to the appropriate item on the screen. The animation therefore was rewound and shown again for just a few seconds. These terms were necessary for answering the questionnaires. A pencil and paper questionnaire with open questions was given to elicit a short description of how the clock functions then an electronic questionnaire was given containing statements to be assessed by the participants for their accuracy. A final questionnaire measured cognitive load.

Measurement

Prior Knowledge Subjects rated their general physics knowledge (based on high school level) and their specific knowledge about mechanics. The seven step scales ranged from 'little' to 'very high'.

Cognitive Load Cognitive load was self-rated by an adapted pencil and paper version of NASA-TLX using five scales with seven steps on mental demands, difficulty, own performance, effort and frustration.

Pointing Each pointing gesture that was clearly directed to pendulum, escapement, chain, weight, second hand, or minute-or-hour-hand was counted, regardless of being accompanied by the mentioning of the appropriate word or not. If two seconds elapsed before or after the pointing gesture, the pointed part was named appropriately, the time stamp of the pointing was adapted to the time of the mentioning.

Mentioning Each mention of the pendulum, escapement, chain, weight, second hand, or minute-or-hour-hand was counted, from either direct mentions or their synonyms. For example 'Schwinger' (oscillator) for pendulum or 'Hemmungsrad' (escape wheel) for escapement. Mentioning of the chain wheel was also counted for the chain.

Concepts Think-aloud protocols and written descriptions were evaluated for the occurrence of correct and false concepts. Negation of a concept was coded in case a subject explicitly negated a concept. Concepts mentioned as part of an explicit question were ignored. The correct concepts taken into account were chosen according to their central importance for a complete description of the basic functional mechanism of the clock (e.g. 'the pendulum hinders the weight from falling down'). There were four different correct concepts for weight and pendulum respectively, and three for escapement. The false concepts were determined by extracting from the transcripts the frequently mentioned false statements about each of the three central clock parts (e.g. 'the weight is for balance'). Four false concepts about the weight, five about the pendulum and three three escapement were coded.

For the purpose of analysis, occurrences of correct and false concepts for each part were counted on a subject level, ignoring repetitions. To compensate for the different numbers of possible correct and false concepts respectively for each part, the ratio of occurring to possible concepts was calculated. If a concept was negated, all previous occurrences of the concept were ignored. For

[1] Available at http://www.blender.org

[2] The first two minutes of the stimulus material are available at http://www.iwm-kmrc.de/cybermedia/cs06-tempo

the verbal reports, if a later-mentioned correct concept implicitly contradicted a previously mentioned false concept, this false concept was not taken into account (e.g. when a subject stated that the weight drives the clock, and had previously stated the same for the pendulum).

Design

The Design was a two groups design with Tempo (normal vs. fast) as independent variable. Within subject variables were Correctness (correct vs. false concepts), and Part (clock parts). For mentioning and pointing, clock parts were the weight, pendulum, escapement, second hand and hour-or-minute hand. For concepts the clock parts were the weight, pendulum, and escapement.

Results

Closed Questionnaires

Prior Knowledge The participants' self-rating of their general and mechanical physics knowledge were well correlated ($r = .68, p < .001$), and were therefore condensed into one overall prior knowledge measure. All analysis using ANOVA were also conducted with prior knowledge as covariant, which reduced the number of significant results in some cases, but never resulted in a previously not already shown effect. Reported results all consider prior knowledge unless otherwise stated.

Cognitive Load Cognitive load measure provided no differences between the subjects in the normal and the fast tempo condition.

Online Measures

Pointing Pointing of the chain and the weight was aggregated, because they are both parts of the same functional component. Overall kappa for pointing was $\kappa = .81$. Two-factorial ANOVA with Tempo x Part showed a significant main effect for Tempo. In the fast condition subjects pointed more often, $F(1, 29) = 4.20, p < .05$.

Mentioning Mentioning was counted for the same clock parts as pointing. Some subjects occasionally fluffed the names for the clock parts (e.g. pointing to the pendulum and saying 'this weight'). If the mentioned word contradicted a concurrent pointing gesture, mentioning was corrected to the pointed clock part. This mismatch appeared for 16 subjects 1 or 2 times and for one subject 6 times. On average, 0.91 mismatches occurred per subject. There was no significant difference between the normal and fast tempo conditions (0.77 and 1.58 mismatches respectively). Overall kappa for mentioning was $\kappa = .93$. Two-factorial ANOVA with Tempo x Part showed no significant main effect, but the interaction of Tempo x Part was significant, $F(4, 116) = 2.84, p < .05$. Pairwise comparison of the two tempo conditions using Sidak showed only in tendency that subjects in the fast condition mentioned the weight more often and the minute or the hour hand more seldom than in the normal condition, $p = .09$ respectively.

Table 2: Pointing and mentioning frequencies for Pendulum, Escapement, Weight, Second hand, and minute-or-hour-Hand (SD in brackets).

	Pointing		Mentioning	
	Normal	Fast	Normal	Fast
P	3.06 (3.26)	5.75 (4.75)	5.88 (4.19)	6.94 (5.21)
E	2.12 (1.54)	3.50 (2.16)	0.06 (0.25)	0.06 (0.25)
W	4.44 (3.10)	7.93 (7.15)	4.88 (3.81)	7.88 (5.38)
S	1.75 (1.91)	3.19 (2.32)	3.63 (2.06)	2.56 (2.63)
H	2.44 (2.37)	2.75 (3.96)	7.00 (3.31)	5.06 (3.07)

Concepts in Verbal Reports Kappa values for concepts in verbal reports were in the range from $\kappa = .73$ to $\kappa = 1.0$, except for escapement with $\kappa = .65$. The percentage of concepts occurring in the verbal reports was evaluated using a three-factorial ANOVA Tempo x Correctness x Part. No main effects were significant. The two way interaction Tempo x Part was significant with $F(2, 58) = 4.88, p < .05$. Three way interaction Tempo x Correctness x Part was significant with $F(2, 58) = 4.41, p < .05$. Pairwise comparisons for the three way interaction using Sidak revealed that for the weight, there were more correct concepts than false concepts in both tempo conditions, normal $p < .05$ and fast $p < .001$. Also, there were more correct concepts for the weight in the fast condition than in the normal condition, $p < .05$.

Table 3: Percentage of concepts in verbal reports for Pendulum, Escapement, and Weight (SD in brackets).

	Correct concepts		False concepts	
	Normal	Fast	Normal	Fast
P	25.0 (22.4)	15.6 (15.5)	20.0 (0.0)	20.0 (12.6)
E	6.3 (13.4)	14.6 (17.1)	8.3 (14.9)	4.2 (11.4)
W	28.1 (31.5)	53.1 (20.2)	10.9 (12.8)	9.4 (15.5)

Open Questionnaire

Concepts in Written Descriptions Kappa values for written descriptions ranged from $\kappa = .78$ to $\kappa = 1.0$. The percentage of concepts occurring in the written descriptions was evaluated using a three-factorial ANOVA Tempo x Correctness x Part. Prior knowledge had no effect on the written descriptions. None of the main effects was significant. Two way interactions of Tempo x Part and Tempo x Correctness were significant with $F(2, 58) = 3.95, p < .05$ and $F(1, 29) = 4.58, p < .05$ respectively. Three way interaction was not significant. For the Tempo x Correctness interaction pairwise comparison using Sidak revealed that subjects in the fast tempo condition wrote significantly more correct concepts, and significantly less false concepts than the normal tempo condition subjects, $p < .05$ in both cases (cf. Table 4). Also only subjects in the fast condition produced significantly more correct than false concepts in their written descriptions, $p < .01$. For the Tempo x Part interaction pairwise comparison using Sidak re-

Table 4: Percentage of concepts in written descriptions.

	Correct concepts	False concepts
Normal tempo	8.9 (SD 13.2)	7.7 (SD 5.5)
Fast tempo	18.4 (SD 12.5)	4.0 (SD 5.8)

vealed that subjects in the fast tempo condition wrote significantly more concepts (either correct or false) about the weight than about any other part, $p < .05$. They also wrote more about the weight than the subjects in the normal tempo condition, $p < .05$.

Discussion

The results support the hypothesis, that variation in presentation speed affects the distribution of attention. Interaction for mentioning of Tempo x Part shows that subjects in the fast tempo condition had a different mentioning profile from those in the normal condition. They tended to mention the weight, which is a central part of the mechanism, more often and the minute or hour hand less often. It is notable that in the normal condition the minute or hour hand is mentioned more frequently, although it is almost static in this condition. This suggests that the attentional profile was not based solely on visuospatial and temporal characteristics, but was also influenced by top-down processes.

The hypothesis that a changed attentional profile has implications for the understanding of the clock is also supported. Subjects' written descriptions of the function of the clock contained more correct concepts and less false concepts for the fast version. In the verbal reports given during animation perception, the number of correct concepts stated for the weight was greater for the fast condition. This is consistent with the idea that the more appropriate conceptualization of the clock in the final descriptions has been achieved by the perceptual guiding of reasoning towards the weight as a key component of the clock's driving mechanism.

Whereas attention was influenced by changed presentation speed, interestingly Cognitive Load appears unaffected. Because the stimulus material contains various temporal levels, this may indicate that speed alteration leads subjects to focus on other parts or other features of the dynamic visualization. Despite the higher density of information in the fast condition, subject's showed superior performance in the understanding task. It may be that subjects regulated their processing load by ignoring fast moving parts, or changed their processing granularity to extract features at a different level (e.g. perceived relative rather than absolute dynamic properties, or segmented the time flow into coarser events).

In sum, the findings suggest that in order to design more effective dynamic visualizations, it may be advantageous to deviate from normal speed presentation if the thematically relevant aspects thereby become more perceptually salient. This first investigative finding opens up a broad field of using temporal manipulations for instructional design. For complex subject matter, it seems possible that speed could be used strategically by instructional designers to raise the perceptual salience of thematically relevant aspects of the display; the optimum speed for revealing key aspects may sometimes be faster, sometimes slower, than realistic speed. The redistribution of attention could also be used on a subject level, by presenting content successively at different presentation speeds. Follow-up studies are needed to explore the combination of various speeds and to obtain more direct evidence of redistribution of attention.

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