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An eye tracking comparison of external pointing cues and internal continuous cues in learning with complex animations

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Abstract

Two experiments used eye tracking to investigate a novel cueing approach for directing learner attention to low salience, high relevance aspects of a complex animation. In the first experiment, comprehension of a piano mechanism animation containing spreading-colour cues was compared with comprehension obtained with arrow cues or no cues. Eye tracking data revealed differences in learner attention patterns between the different experimental conditions. The second experiment used eye tracking with synchronized and non-synchronized cues to investigate the role of dynamic direction of attention in cueing effectiveness. Results of Experiment 1 showed that spreading-colour cues resulted in better targeting of attention to thematically relevant aspects and in higher comprehension scores than arrow cues or no cues. For Experiment 2, superior comprehension after the synchronized version together with eye tracking data indicated that cue effectiveness depended on attention direction being spatially and temporally coordinated with onsets of animation events having high thematic relevance to the learning task. The findings suggest the importance of perceptual cues and bottom-up processing.

Keywords: Animations; Cueing; Perceptibility profile; Attention guiding; Eye tracking

1. Introduction

Animated graphics have no clear intrinsic superiority over their static counterparts (Bétrancourt, 2005; Tversky, Bauer-Morrison, & Bétrancourt, 2002). Further, evidence is accumulating that animations can pose their own distinctive challenges to learners (Höffler & Leutner, 2007; Lowe, 2001, 2004a; Lowe & Schnotz, 2008).

As the visuospatial and temporal complexity of an animated display increases, there can come a point where the processing demands of the learning task become excessive (Ayres & Paas, 2007). Beyond this threshold, learners who are not equipped to ameliorate these demands are likely to become progressively less able to deal with the presented information effectively (Kriz & Hegarty, 2007). In order to maintain their processing, they may adapt to this situation by adopting approaches for reducing the processing demands so as to make the task tractable. For example, it has been found that novice learners take a highly selective approach in which their processing favours the more perceptually salient aspects of the animation to the neglect of the rest of the display (Lowe, 2003). This may jeopardize learning effectiveness because perceptual salience is not necessarily aligned with thematic relevance (Lowe, 2005).

1.1. Perceptual salience vs. thematic relevance

Schnotz and Lowe (2008) have distinguished two major contributors to the relative perceptibility of entities that make up an animation. One is *visuospatial contrast*, that is, if an entity is relatively large, brightly coloured, unusually shaped, and centrally placed, it is likely to be more readily perceived than its less distinctive neighbours. The second is *dynamic contrast*, that is, the perceptibility of a specific entity may be

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enhanced if it is moving or changing over time in a manner that contrasts greatly with the behaviour of entities in its neighbourhood (Lowe, 2005). The combined effects of visuospatial and dynamic contrast mean that the component entities of an animation can range across a wide spectrum of perceptibility. This overall range constitutes a *perceptibility profile* that is characteristic of a particular animated display. Ideally, the natural perceptibility profile of the entities constituting an animation would correspond with their relative importance to the central theme of the learning task. In practice, perceptibility and relevance are too often misaligned characteristics within educational animations, thus, learners' extraction of key task-relevant information is likely to be compromised.

For learning tasks that focus on understanding of mechanical (or technical) systems, thematic relevance is typically concerned with matters such as the components and relationships that are fundamental to the causal chains upon which the system's functioning depends. Moreover, aspects having high thematic relevance in an early stage of a process may have a lower thematic relevance at some later stage, and vice versa.

There is relatively little guidance available in the research literature on how to support effective animation processing. We proposed a five-phase hierarchical model characterizing learning from complex animation as a cumulative process for building dynamic mental models that involves both analysis and synthesis and emphasizes the influence of bottom-up processes (Lowe & Boucheix, 2008).

1.2. Perceptibility profile of a piano mechanism

A traditional piano mechanism exhibits the type of temporal variation in thematic relevance referred above in the introduction. The two empirical studies reported in this article concern an animation (without text) of an upright piano's hidden mechanism, a subject-matter that is both complex and unfamiliar to most people. However, in the piano animation, all the entities and related events are perceptually available to the learners. The internal mechanism by which a note is produced when a pianist presses a key on a piano keyboard consists of a complex system of levers and pivots (Fig. 1).

In operation, the piano mechanism involves a hierarchical set of interdependent events that occur rapidly and overlap in time. These individual events concern the actions of two closely interrelated functional subsystems. The more fundamental of these is the hammer subsystem by which the motion of the key press is amplified and transferred to a felt-covered hammer that strikes the corresponding string so producing the required note (see Appendix and Fig. 3 for a description of the name of the components). A second subsystem involving a sound damper works in close association with the hammer action to prevent prolonged vibration of the string once it has been struck (for purposes such as maintaining musical clarity across successive notes). However, when the key for any one of the strings is depressed, its damper must be removed before the corresponding hammer strikes the string so that the note is free to sound. Then, once the pianist releases the key to end the note, the damper must immediately return to its original position on the string to cut off the sound.

Each complete operational cycle of the piano mechanism can be summarized in terms of three main stages: (a) Stage 1: striking the string with the hammer; (b) Stage 2: rebounding and recovering from the strike; (c) Stage 3: resetting the mechanism ready for the next strike (see Appendix and Fig. 3). The hammer subsystem and the damper subsystem each involve a multiple element causal chain that runs between the key and either the hammer or the damper. These two causal chains must work in a tightly integrated manner if the piano is to function correctly and reliably, especially when playing rapid sequences of notes is required. The characteristics of a piano mechanism animation that are likely to pose significant processing challenges to learners include: (a) the rapid succession of events occurring during the mechanism's operation, (b) the multiple and widely distributed sites of thematically relevant action across the animated display, (c) the presence of crucial but highly transitory conjunctions that are easily missed if not specifically attended to at just the right moment, and (d) the continuous nature of the changes that are involved (cf., Lowe, 1999).

Concerning the perceptibility profile of the piano mechanism animation, this mechanism has a high degree of behavioural realism (Lowe, 2005) in that the actions portrayed closely reflect the nature, sequence, relative duration, and extent of the movements of an actual piano mechanism. Both the basic visual properties of the component graphic entities (an array of six main graphic entities) and their behaviour contribute to potentially problematic misalignments of perceptual salience and thematic relevance. For example, the hammer has a high level of perceptibility because it is a large, distinctively-shaped item whose movement is rapid and covers much of the display area. Although the hammer plays a central function in making the string sound, its successful operation depends on parts of the mechanism with far lower conspicuity (such as the whippen[1] or the jack, components that in relative terms are small, visually less remarkable, and move but slightly). For a learner's mental model of the piano mechanism's functioning to be an adequate basis for proper understanding, it needs to include information about both the more obvious operational components (e.g., the hammer and the damper) and the crucial but visually inconspicuous aspects (e.g., the whippen and the jack) upon which their successful operation depends.

Another source of challenge for learners is that the relative importance of each of the piano mechanism's various components changes over the time course of its operation. For example, the balance hammer back-check contributes its functionality only in the later half of the mechanism's

[1] In the musical domain the English word *whippen* (in Dutch "*wippen*") is usually used as a synonym of the word "bridge", in order to name the component which make the linking between the key and the two subsystems of the piano mechanism, the damper subsystem which operates via the spoon and the hammer subsystem which operates via the jack.

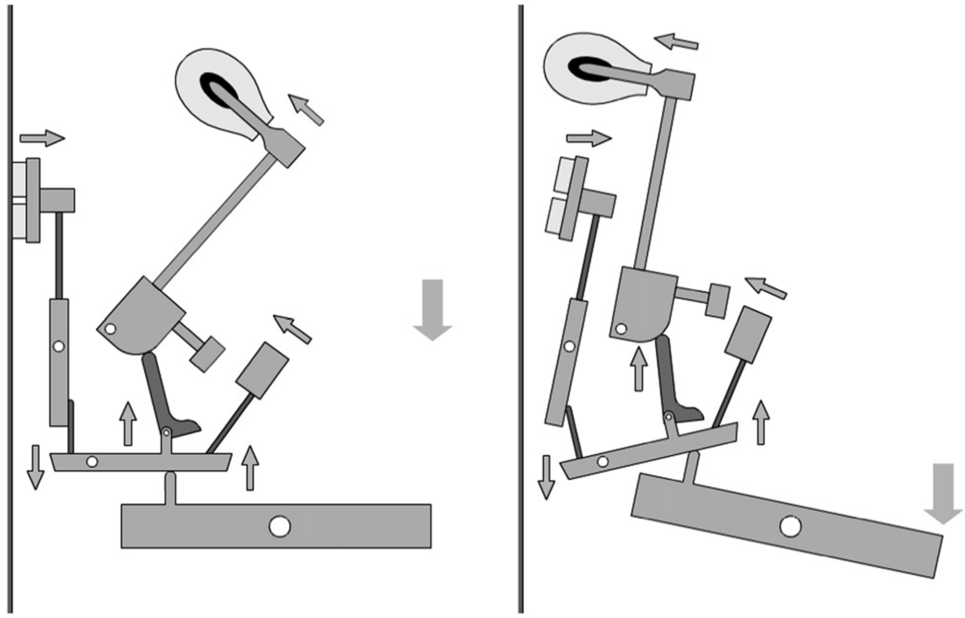

Fig. 1. Piano system with arrows indicating movement of parts.

operational cycle. To understand this contribution, the learner therefore needs to direct attention to this component at just the right time.

A learner's exploration of the animation should be one that facilitates extraction of information concerning the causal chains that are fundamental for the piano's operation. To follow the progress of these two causal chains, the learner would need to begin by directing attention to the part of the display in which the causal chains originate. Both causal chains are initiated when the piano key is pressed so it is in this region of the animated display that learner attention should first be directed. Particular attention needs to be given to the small projection on the end of the key that contacts the whippen slightly off centre (Figs. 1 and 3). However, *attention capture* alone is insufficient. The learner's attention must also be transferred between different attention sites in an appropriate sequence and at a suitable rate, that is, effective *attention guidance* is essential.

1.3. Directing learners' attention with cueing techniques

The experimental work reported here examines a new cueing technique designed to direct learner attention efficiently. A number of approaches have been investigated for helping novices to process complex animations more effectively. These range from learner-oriented support such as the provision of user-control (Boucheix, 2008; Lowe, 2004b) to design-oriented interventions, such as temporal manipulation of the presentation regime (Fischer, Lowe, & Schwan, 2008; Lowe & Schnotz, 2008; Meyer, Rasch, & Schnotz, 2010). A type of design-oriented intervention that has a long history in the field of static graphics is the use of visual cues to direct learner attention to key aspects of a display (Mautone & Mayer, 2007; Mayer, 2001; Tversky, Heiser, Lozano, MacKenzie, & Morrison, 2008). Arrows are a ubiquitous form of cue used to indicate which locations in the display contain relevant information and therefore merit attention by the learner. However, it is possible that cues found to be effective in static graphics may lose their potency when used with animations (Kriz & Hegarty, 2007). Further, in animations arrows can lack the precision required for directing learner attention effectively (De Koning, Tabbers, Rikers, & Paas, 2007, 2010; Kriz & Hegarty, 2007). For example, consider an arrow that is used as an exterior pointer in a display to indicate internal aspects of the subject-matter. Although using this external indicator has the advantage of not obscuring the targeted aspect, it can be ambiguous in terms of exactly what the learner should attend to. Another potential problem with arrows, particularly for low spatial ability learners, concerns difficulties in coordinating the meaning of multiple arrows in a diagram.

For information extraction to be effective, it is crucial that learner attention be directed to precisely the right locations in the animation at precisely the right times (Lowe, 2008). However, the many misalignments between perceptual salience and thematic relevance in the piano mechanism and its operation would be expected to make it difficult for a learner to obtain the required spatial and temporal precision. One possible approach for ameliorating the misalignments between perceptual salience and thematic relevance in the piano mechanism and its operation would be to use visual cues (typically assumed to be non-content devices such as arrows, highlighting etc., that are added to the display) to reduce the search space, a learner must explore and so increase the likelihood that task-relevant activity sites will receive due attention. In static depictions of dynamic content, arrows can indicate the presence of motion. If arrows are included in an animation that already provides an explicit representation of movement, their primary function may not be to indicate motion as it is with static graphics. Rather, their chief effect could be to cue key aspects of that depicted motion.

1.3.1. Point vs. continuous cueing

However, a conventional arrow does not provide continuous path information and so lacks explicitness with respect to the propagation of causal chains through a series of event units. With complex animations, learners are likely to require more spatially and temporally precise support in order to help them process the displayed material, to produce and organize the required local event units (Mautone & Mayer, 2007), and then to progressively link these via the formation of larger units into a coherent initial mental representation.

A possible alternative to the external point cues provided by arrows is internal continuous cueing in which on-going dynamic guidance information is incorporated within high relevance entities that require learner attention. We have devised an approach for providing this internal continuous cueing that will be referred to as ‘‘spreading-colour cues’’. In this form of cueing, high perceptibility ribbons of colour overlaid on the depicted material spread through the animation's most thematically relevant graphic entities in synchrony with the propagation of the main causal chains via those entities (Fig. 2). Because these conspicuous continuous spreading-colour cues have a close spatial and temporal fit to high relevance information in the display, they should improve learners' information extraction in a number of ways. These include: (a) supporting more efficient and effective search due to reduction of search space, (b) counteracting the otherwise dominant effect of high perceptual salience aspects so that they do not out-compete important but inconspicuous aspects for learner attention, and (c) guiding learner attention in a way that is spatially and temporally aligned with the animation's presentation of key information.

1.4. Eye tracking to investigate animation processing

The great majority of previous animation research has used off-line written tests to measure comprehension performance. As a result, we know little about the on-line processing of animations across space and time. More immediate data gathering approaches have been gaining favour (Jarodzka, Scheiter, Gerjets, & Van Gog, 2010; Kriz & Hegarty, 2007; Lowe, 2004a; Schneider & Boucheix, 2006). The studies reported here used eye tracking to investigate learners' on-line processing as they extracted information from an animated presentation in preparation for a subsequent off-line written comprehension test.

2. Experiment 1

Experiment 1 compared the effect of three cueing conditions: (a) an arrow cue condition, (b) a spreading-colour cue condition, and (c) a no-cue condition on comprehension and the orientation of attention during learning of the animated piano mechanism.

With regard to comprehension, it was predicted that learners in the spreading-colour cue condition would outperform those in the arrow cue condition and that learners in the arrow cue condition would outperform those in the no-cue condition (Hypothesis 1).

It was also predicted that eye tracking measures would reveal that learners in the different conditions exhibit different patterns of attention direction relative to specific parts of the piano mechanism. In particular, it was expected that spreading-colour cueing would be more effective than arrow cueing and that arrow cueing would be more effective than no cueing in directing learner attention to thematically relevant components of the mechanism (such as the whippen) and so reduce misalignments between thematic relevance and perceptual salience (Hypothesis 2).

2.1. Method

2.1.1. Participants

Participants in Experiment 1 were 57 undergraduate students (5 males and 52 females, which is the usual composition for the Psychology Departments in France) with a mean age of 20.7 years ($SD = 3.27$); they participated for course credit. Before the experiment, participants were asked about their possible task-specific prior knowledge. None of the participants selected for the experiment had prior knowledge about mechanical piano systems.

2.1.2. Apparatus and materials

2.1.2.1. Animation. Three versions of a computer-based user-controllable piano system animation were employed: (a) a non-cued version, (b) a version with dynamic arrows (Fig. 1), and (c) a version of continuous spreading-colour cues (Fig. 2). There was no explanatory text accompanying the animation. However, in all versions, pop-up labels showing piano part names were available to be viewed at any time via computer mouse roll-over. The arrow version was cued with a series of arrows placed alongside main parts of the piano system to indicate the direction in which each of these parts moved. These arrows were dynamic and their onset synchronized with learners' control of the animation. They, thus, appeared progressively in a manner similar to the progressive development of the continuous spreading-colour cues that will now be described. When a participant used the computer mouse to ‘press’ the piano key in this third version, a spreading-colour cue appeared and traced ‘high relevance’ paths through components of the mechanism (Fig. 2).

Progress of the spreading-colour cue trace was synchronized with the learner's exercise of user-control. The cue's path followed causal chain propagation, thus indicating to the learner ‘‘when to look and where to look’’ (Lowe, 2008). Two contrasting colours (blue and red) were used to divide the cueing between the piano's two main functional sub-mechanisms: the hammer subsystem and the damper subsystem. In addition to the continuous spreading-colour cues, two ‘instantaneous’ (very brief) cues were incorporated at appropriate places in the sequence to signal impact events: the hammer impact and the balance-back-check impact

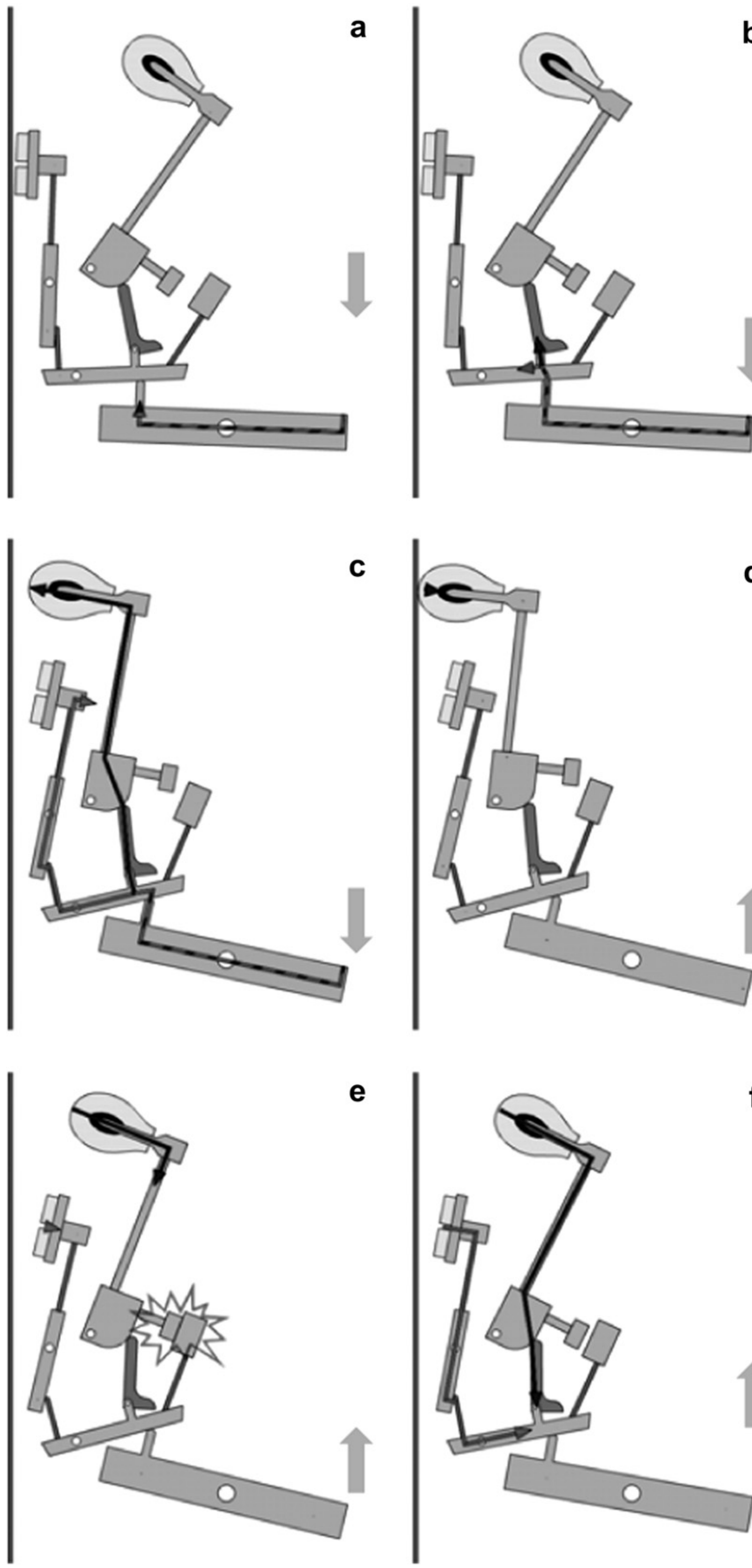

Fig. 2. (a–f) The spreading-colour cue.

(Fig. 2, picture 5e). The intended purpose of these impact cues was to provide punctuation points embedded within the flow of the spreading-colour cues to signal discrete rather than continuous sequential aspects.

2.1.2.2. *Spatial ability test*. An abbreviated (Part 4: Spatial relations) French form of the differential aptitude test (DAT, Bennett, Seashore, & Wesman, 1973, 2002) was used to measure spatial ability. The Spatial Relations test (Booklet 4) measured mental rotation ability for figures. The median for our sample was 56.66% correct answers ($M = 59.35\%$, $SD = 22.32$). Note that with a 56% median score, the spatial abilities of the participants of our study were situated within the sixth level out of eleven according to the French reference normalization table (Bennett et al., 1973, 2002, normalization table, p. 74). It should be also noted that the representative sample used for the French reference normalization of the DAT test (French adults, superior to advanced level, 50% females and 50% males; Bennett et al., 1973, 2002, p. 46) scored an average of 42.83% for females and 55.33% for males for spatial relations and mechanical reasoning combined. Therefore, the spatial abilities of our sample, mainly composed of females, appeared to be much closer to the male rather than to female population of the French normalization tables.

2.1.2.3. Comprehension test. Comprehension was measured using three types of items, each focusing upon one of the different levels of information identified by Narayanan and Hegarty (1998). The items concerned (a) the configuration of the piano system's parts (7 items, e.g., "Which parts touch the key?"; "The whippen touches the spoon" True or false?), (b) the local kinematics of the system with respect to both the presence and direction of motion of each part (16 items, e.g., "Does the whippen move? If yes, up or down?"; "The damper causes the striking of the hammer on the string? False or true?"), and (c) the overall functional mental model of the piano system involving integration of all component parts and kinematics (e.g., "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"). Answers to these different item types produced comprehension sub-scores for (a) configuration, (b) local kinematics, and (c) functional mental model quality.

For configuration and local kinematics, answers were right or wrong regarding the concrete objective behaviour or position of each component of the piano mechanism. So, scoring was based on a predetermined grid of right and wrong answers and the interrater agreement between two independent raters was perfect.

The functional mental model quality scoring guide was based on the 15 micro-steps constituting the three main stages of a piano mechanism's functioning (see Appendix). Each correct micro-step was awarded one point if fully and precisely 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; interrater agreement, chance corrected Cohen's kappa, was 0.94.

Scores on each measure (configuration, kinematics, and functional model) were transformed into percentages of total possible score on sub-measures (i.e., configuration, kinematics, and functional model).

2.1.2.4. Eye tracking equipment. Eye movements were recorded with a 50 Hz ASL 5000 corneal reflectance and pupil centre eye tracker. This system utilizes a magnetic head tracker. Data were recorded with GazeTracker software. The computer screen for displaying the animation was positioned approximately 60 cm from the participant.

Several eye tracking indicators were employed on the basis of nine areas of interest (AOIs), each of which corresponded to a functionally relevant part of the piano system (Fig. 3). The type and size of the AOIs chosen across the display were the same for all three conditions. Each of these AOIs was defined with sufficient scope to include both the arrow and the spreading-colour cue in the cued conditions, and the boundaries of the particular piano part's entire movement during its operational cycle. Two main types of data are widely collected in eye tracking investigations (Rayner, 1998): (a) the number of fixations in different AOIs, and (b) the total duration of fixations in different AOIs. The fixation filtering threshold was set at 100 ms.

2.1.3. Procedure

Participants were first tested for spatial ability. Based on a median split, they were divided in low and high spatial ability groups. Within those two groups, participants were then randomly assigned to one of the three conditions ($n = 19$ per condition).

The experiment was run on an individual basis with participants seated at the computer and instructed to study the animation in order to understand the depicted mechanism in preparation for a subsequent comprehension test. The eye tracker was calibrated for each participant immediately prior to the session. No limit was placed on animation study times, but participants were required to study the animation at least three times. After having completed their study of the animation, participants completed the comprehension test.

2.2. Results

2.2.1. Learning time

The piano animation was fully controllable, leading to possible study time differences between participants. Cued conditions could also lead to longer learning times (see Boucheix & Guignard, 2005). Thus, we first checked the effect of cue types on learning time. An ANOVA, with cue type as the between subjects factor and total learning time (in seconds) with the animation (determined from eye tracking data) as dependent measure showed a marginal effect of cueing $F(2, 54) = 3.06$, $p = 0.055$, partial $\eta^2 = 0.10$. Follow-up planned contrasts showed that learning times were higher for the two cued conditions (for arrow cues $M = 232.90$, $SD = 115.70$; for spreading-colour cues $M = 245.13$, $SD = 110.10$) than for the no-cue condition ($M = 166.80$, $SD = 0.87$), $F(1, 54) = 5.99$, $p = 0.018$, partial $\eta^2 = 0.10$. There was no significant difference between the arrow and spreading-colour cue conditions, $F(1, 54) < 1$, ns. Given these effects of cueing, and the fact that learner control could also lead to variations in learning time, learning time was systematically used as a continuous covariate factor in all analyses reported below.

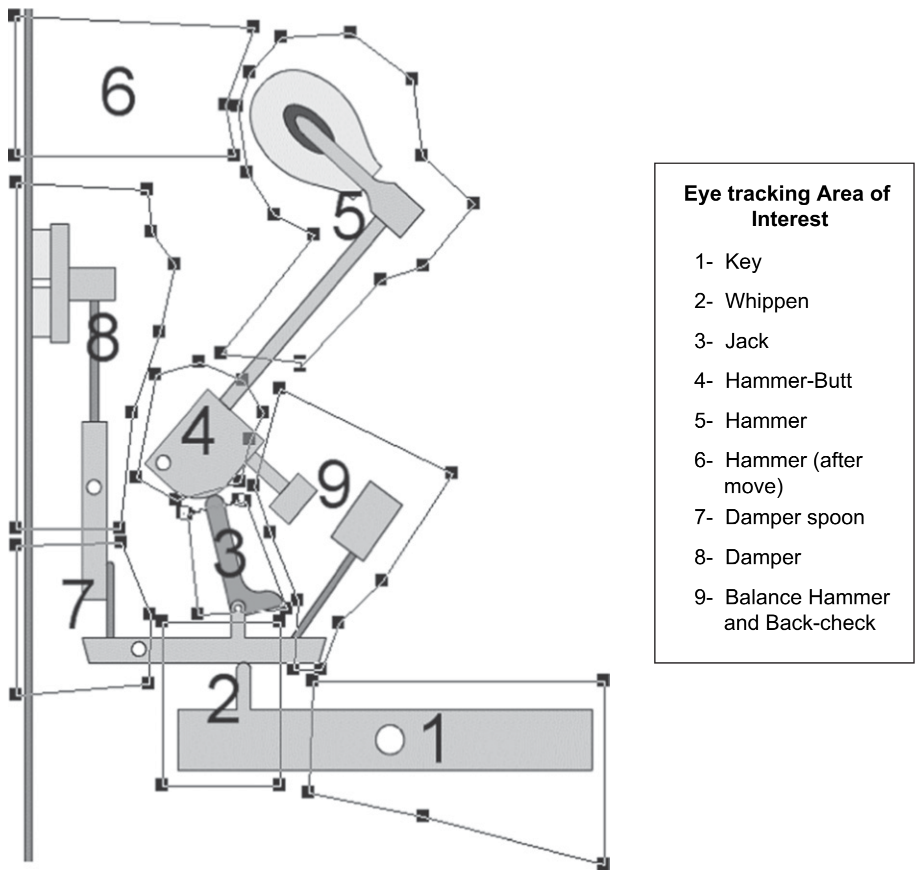

Fig. 3. The nine areas of interest for different piano mechanism parts.

2.2.2. *Comprehension measures*

Table 1 shows the variation of comprehension performance in configuration, kinematics, and functional mental model quality as a function of cue condition. A repeated measures ANCOVA using learning time as covariate factor, cue type (no cue, arrow cue, and spreading-colour cue) as the between subjects factor and comprehension scores (configuration, local kinematics, and functional mental model quality) as within subjects factor showed no effect of learning time, $F(3, 51) = 1.21$, ns, but significant main effects for cueing condition, $F(2, 53) = 3.47$, $p = 0.038$, partial $\eta^2 = 0.12$, and for types of comprehension scores, $F(2, 106) = 44.39$, $p < 0.001$, partial $\eta^2 = 0.45$. For factor cue type, planned contrasts revealed that the spreading-colour group outperformed the arrow group, $F(1, 53) = 6.04$, $p = 0.017$, partial $\eta^2 = 0.10$, but the arrow group did not differ significantly from the non-cued group, $F(1, 53) = 0.10$, ns. The interaction between cue type and comprehension measures was significant, $F(4, 106) = 4.21$, $p < 0.01$, partial $\eta^2 = 0.14$.

Table 1
Means in percent (and SD) for the three comprehension measures as a function of the three cueing conditions of Experiment 1.

Comprehension measure	Cueing conditions		
	No cue	Arrow cue	Spreading-colour cue
Configuration	64.66 (17.41)	66.16 (20.32)	60.90 (21.2)
Local kinematics	58.88 (11.28)	61.84 (13.64)	75.65 (10.39)
Functional mental model quality	14.39 (12.57)	9.5 (11.56)	25.26 (11.67)

Moreover, three separate univariate ANCOVAs, including learning time as covariate and cue type as a between subject factor, were performed for each type of comprehension score. In the case of configuration, the ANCOVA showed no significant effect for cue type, $F(2, 53) < 1$, ns, for local kinematics; however, a significant effect of cue type was found, $F(2, 53) = 9.30$, $p < 0.001$, partial $\eta^2 = 0.26$. Planned contrasts showed that participants in the spreading-colour cue condition ($M = 75.65$, $SD = 10.39$) outperformed those in the arrow cue condition ($M = 61.64$, $SD = 13.64$), $F(1, 53) = 12.52$, $p < 0.001$, partial $\eta^2 = 0.19$, but there was no significant difference between performance in the arrow cue ($M = 61.84$, $SD = 13.64$) and the no-cue condition ($M = 58.88$, $SD = 11.28$), $F(1, 53) < 1$, ns. Regarding the functional mental model quality scores, significant effects were found for cue type, $F(2, 54) = 8.19$, $p < 0.001$, partial $\eta^2 = 0.24$. Planned contrasts revealed that participants in the spreading-colour cue condition ($M = 25.26$, $SD = 11.67$) outperformed those in the arrow cue condition ($M = 9.50$, $SD = 11.56$), $F(1, 53) = 16.19$, $p < 0.001$, partial $\eta^2 = 0.23$, but there was no significant difference between performance in the arrow cue ($M = 9.50$, $SD = 11.56$) and the no-cue condition ($M = 14.39$, SD $= 12.57$), $F(1, 53) = 2.26$, ns. Thus, the interaction between cue type and comprehension scores signified that the significant positive effect of the spreading-colour cue was only found for the kinematics and functioning-mental model quality scores but not for the configuration score.

2.2.3. Eye tracking data

Table 2 presents mean numbers of fixations in the nine AOIs, for each condition. In order to test our hypothesis regarding alignments and misalignments of the components of the piano mechanism with their functional importance, the nine AOIs, were assigned to three categories with respect to their relative thematic relevance and relative perceptual salience. This categorization was based on experts' descriptions derived from previous work on the piano mechanism (Lowe & Boucheix, 2008) and general principles regarding visuospatial and dynamic contrast (Lowe & Schnotz, 2008). This latter aspect of categorization took account of aspects such as the size, position, appearance and movement of display components (differences in AOI's sizes was also controlled for). The first category grouped components with low perceptual salience (LPS) but high thematic relevance (HTR), that is, whippen, end of the key, and spoon (LPS/HTR). The second category grouped components with medium perceptual salience (MPS) and high thematic relevance, that is, jack and butt (MPS/HTR). The third category grouped components with high perceptual salience (HPS) but low thematic relevance (LTR), that is, hammer, damper, and balance-back-check system (HPS/LTR).

A repeated measures ANCOVA, using learning time as the covariate factor, cue type as the between subjects factor and the three categories (LPS/HTR, MPS/HTR, HPS/LTR) as within subjects factor was performed. Results showed a main effect of learning time on fixation number, $F(1, 53) = 475.64$, $p < 0.001$, partial $\eta^2 = 0.89$ (this is a mechanical effect of study time on eye fixations), and no effect of cue type on the overall fixation number, $F(2, 53) = 0.90$, ns. There was, however, a significant interaction between cue type and categories, $F(4, 106) = 3.07$, $p = 0.019$, partial $\eta^2 = 0.10$. Participants in the spreading-colour cue condition spent more time than those in either of the other two conditions, fixating on LPS/HTR category, $F(1, 54) = 5.99$, $p < 0.05$. Data also showed a significant interaction between learning time and categories, $F(2, 106) = 14.81$, $p < 0.001$, partial $\eta^2 = 0.22$. The direction of this interaction indicated that the effect of learning time on fixation number is higher for the HPS/LTR and MPS/HTR categories than for the LPS/HTR category. This result suggests that the effect of the cueing device (in particular the spreading-colour cue) influenced information processing location early in the study of the animation.

The mean numbers of fixations in AOIs were highly correlated with the total fixation durations, $r(56) = 0.94$, and analyses performed on the fixation durations measure revealed exactly the same pattern of results as for the number of fixations measure and are therefore not reported here.

Table 2
Means and (SD) of number of fixations in the nine AOIs as a function of the three cueing conditions of Experiment 1.

AOIs	Cueing conditions		
	No cue	Arrow cue	Spreading-colour cue
Key	11.94 (13.02)	12.05 (11.96)	28.21 (21.63)
Whippen	32.36 (47.18)	33.68 (24.78)	56.52 (52.72)
Jack	30.63 (21.65)	44.84 (28.21)	40.58 (25.96)
Hammer-butt	35.52 (28.10)	59.70 (44.8)	47.05 (25.77)
Hammer	29.68 (19.28)	43.36 (29.62)	44.15 (19.13)
Hammer-move	21.52 (16.06)	23.42 (13.31)	27.53 (19.97)
Damper-spoon	5.79 (8.32)	11.05 (14.36)	9.42 (8.4)
Damper	56.16 (36.58)	68.31 (52.1)	67.80 (38.73)
Balance and back-check	42.00 (32.09)	74.73 (51.20)	47.00 (22.16)

2.2.4. Eye tracking data and comprehension

To study possible links between eye tracking measures and comprehension measures in the different cue type conditions, a regression analysis was performed. A general regression model (Statistica® GRM) was used, with a mediation analysis plan, with number of fixations in each of the different AOIs as continuous predictor variables, cue type as categorical predictor factor, and comprehension measures (configuration, kinematics and functional model) as dependent variables. This analysis showed a significant relationship between comprehension and the number of fixations in AOIs containing the whippen, $F(3, 43) = 4.07$, $p = 0.012$, partial $\eta^2 = 0.22$, the hammer, $F(3, 43) = 5.45$, $p = 0.003$, partial $\eta^2 = 0.27$, and, to a lesser extent, the damper, $F(3, 43) = 2.84$, $p = 0.05$, partial $\eta^2 = 0.16$.

2.3. Discussion

Hypothesis 1 was supported with the use of continuous spreading-colour cues resulting in overall comprehension scores that were superior to those obtained in the no-cue and arrow cue conditions: Spreading-colour cues positively affected the kinematics and functional mental model quality scores. However, contrary to Hypotheses 1 and 2, we did not find a difference between the arrow and no-cue conditions. Eye tracking results suggest a possible explanation for these differences in comprehension. Both the arrow and spreading-colour cue conditions had greater fixation numbers and durations than the non-cued condition. From this finding, it could be inferred that both types of cues were capable of re-directing learner attention within the animation.

However, it is not sufficient merely to increase the overall number of fixations; rather, the design of the animation must be manipulated in ways that result in a greater number of *appropriately located* fixations. A breakdown of fixations, according to the LPS/HTR, MPS/HTR, and HPS/LTR categories, showed differences in the distribution of these numbers of fixation in the cueing conditions. As predicted by Hypothesis 2, there were more fixations on the LPS/HTR category (e.g., key, whippen), compared to the others categories, in the spreading-colour cue condition, even with learning time as a covariate factor. However, MPS/HTR category was similarly fixated in both spreading-colour cue and arrow cue conditions. It might be a rather surprising finding that fixations on the hammer and the damper, which are highly salient components, but belong to the low thematic relevance areas, significantly correlate with comprehension. In fact, hammer and damper are crucial components of the mechanism, in order to produce the sounds, but they do not constitute the core of the causal chain of the device, contrary to whippen or jack.

3. Experiment 2

In Experiment 1, the dynamic progression of the cues delivered during learners' study of the animation was synchronized with user-control of the display. This synchronization is likely to help learners' coordination of crucial spatial and temporal information by supporting a task-appropriate inspection regime (*where* and *when* to look). The second experiment investigated the effect of synchronization between user-control and cue delivery on comprehension by comparing synchronized and non-synchronized versions of cued piano animations, using both process (eye tracking) and outcome (comprehension) measures.

We hypothesised that synchronized cueing versions should be more efficient for comprehension than non-synchronized versions (Hypothesis 3) and that the synchronized form of the spreading-colour cues should enhance direction of attention through thematically relevant components (Hypothesis 4).

3.1. Method

3.1.1. Participants

Participants in Experiment 2 were 53 undergraduate students (11 males and 42 females, which is the usual composition for the Psychology Departments in France) with a mean age of 20.9 years ($SD = 5.16$); they participated for course credit. None of these students had participated in Experiment 1, and none of them had prior knowledge about the piano mechanism.

3.1.2. Materials

3.1.2.1. Spatial ability test. The same test as in Experiment 1 was used. The median for our sample was 60% correct answers ($M = 59.05\%$, $SD = 19.07$). Note that with a 60% median score, the spatial abilities of the participants of our study were situated within the sixth level out of eleven according to the French reference normalization table (Bennett et al., 1973, 2002, normalization table, p. 74) as in Experiment 1. Therefore, the spatial abilities of our second sample, also mainly composed of females, appeared to be much closer to the male rather than to female population of the French normalization tables.

3.1.2.2. Comprehension test. The same test and scoring grids as in Experiment 1 were used. For the functional mental model quality, interrater agreement, chance corrected Cohen's kappa, was 0.92.

3.1.2.3. Eye tracking equipment. The same equipment as in Experiment 1 was used.

3.1.2.4. Animation. Two factors were studied. Specifically, the cue types used were the same as in Experiment 1 (arrows, spreading-colour). In the synchronized arrow cue condition, onset of the arrows was synchronized with the user-control so that they appeared progressively as the learner pressed the piano's key. In the non-synchronized arrow cue condition, all arrows appeared immediately after the key was pressed and were continuously displayed thereafter. An analogous approach was used for the spreading-colour cue condition. In the synchronized condition, the spreading-colour cueing advanced or retreated in concert with user-control, while in the non-synchronized condition, the complete pattern of cueing appeared at once and persisted (Fig. 4).

3.1.3. Design – procedure

A 2×2 factorial design was used with factors cue type (arrows vs. colour spreading) and user-control synchronization (synchronized vs. non-synchronized). Again, participants were categorized as either high or low spatial, and were then assigned randomly to one of the four conditions: (a) spreading-colour cue plus non-synchronized user-control ($n = 14$), (b) arrow cue plus non-synchronized user-control ($n = 12$), (c) spreading-colour cue plus synchronized user-control ($n = 14$), and (d) arrow cue plus synchronized user-control ($n = 13$).

3.2. Results

3.2.1. Learning time

The ANOVA performed with cue type and synchronization as between subjects factors and total learning time (in seconds) with the animation (determined from eye tracking data) as dependent variable revealed no main effect of synchronization, $F(1, 48) = 3.27$, $p = 0.076$, or of cue type, $F(1, 48) = 1.72$, ns.

3.2.2. Comprehension measures

Table 3 presents the comprehension scores from each experimental condition. A repeated measures ANCOVA with learning time as continuous covariate factor, cue type and synchronization as between subject factors, and comprehension measures as within subjects factor, showed a marginal effect of learning time, $F(1, 47) = 3.78$, $p = 0.058$, partial $\eta^2 = 0.07$, and a nonsignificant effect of synchronization, $F(1, 47) < 1$, ns. However, a main effect of cue type in favour of the spreading colour cue type, $F(1, 47) = 18.38$, $p < 0.001$, partial $\eta^2 = 0.28$, and a main effect of the type of comprehension measure, $F(2, 94) = 23.05$, $p < 0.001$, partial $\eta^2 = 0.33$, were found. There was, also, a significant interaction between synchronization and comprehension measures, $F(2, 94) = 4.99$, $p = 0.008$, partial $\eta^2 = 0.10$.

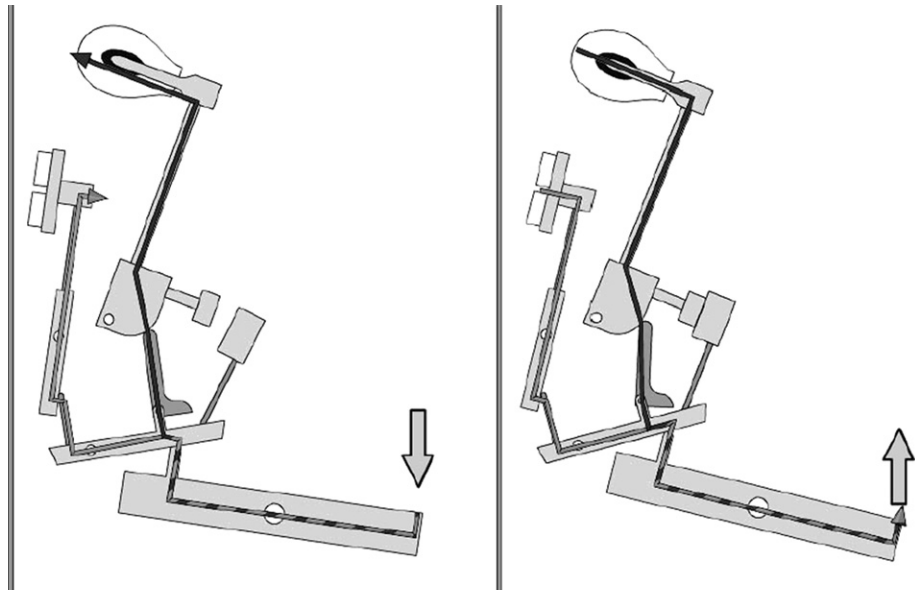

Fig. 4. Non-synchronized appearance of the cues.

Moreover, three separate univariate ANCOVAs, including learning time as covariate, and synchronization and cue type as between subjects factors, were performed for each type of comprehension scores. For configuration scores, ANCOVA showed no significant main effect for synchronization, $F(1, 47) = 2.39$, $p = 0.12$, and a marginal effect for cue type, $F(1, 47) = 3.80$, $p = 0.058$, partial $\eta^2 = 0.05$, favouring the spreading-colour cue condition. For kinematic scores, the ANCOVA showed significant main effect for synchronization in favour of the synchronized condition, $F(1, 47) = 7.17$, $p < 0.01$, partial $\eta^2 = 0.13$, and for cue type in favour of the spreading-colour cue condition, $F(1, 47) = 15.48$, $p < 0.001$, partial $\eta^2 = 0.25$. With respect to functional mental model quality scores (especially Stage 1), ANCOVA revealed that there was a nonsignificant effect of synchronization, $F(1, 47) = 3.38$, $p = 0.072$, but a significant main effect of cue type in favour of the spreading-colour cue condition, $F(1, 47) = 8.29$, $p = 0.006$, partial $\eta^2 = 0.15$. Thus, the interaction signified a significant difference in performance between synchronized and non-synchronized conditions (favouring the synchronized condition) for the kinematic and functional mental model quality scores but not for the configuration score.

Table 3
Means in percent (and SD), for the three comprehension measures as a function of the two cueing conditions in the user-control synchronized and user-control non-synchronized versions of the animation of Experiment 2.

Comprehension measure	Cueing conditions	
	Arrow cue	Spreading-colour cue
Non-synchronized		
Configuration	55.95 (16.63)	59.18 (23.68)
Local kinematics	53.64 (7.28)	63.40 (11.97)
Functional mental model quality	23.05 (8.70)	26.90 (10.66)
Synchronized		
Configuration	45.05 (17.34)	58.16 (19.78)
Local kinematics	61.54 (12.97)	74.10 (10.64)
Functional mental model quality	24.87 (6.75)	33.81 (9.23)

3.2.3. Eye tracking data

Table 4 presents the mean number of fixations for the nine AOIs in each of the cueing and synchronization conditions.

As in Experiment 1, the nine component AOIs were categorized with respect to their relative perceptual salience and relative thematic relevance, that is, LPS/HTR, MPS/HTR, and

Table 4
Means and (SD) of number of fixations in the nine AOIs as a function of the two cueing conditions in the user-control synchronized and user-control non-synchronized versions of the animation of Experiment 2.

AOIs	Cueing conditions	
	Arrow cue	Spreading-colour cue
Non-synchronized		
Key	12.75 (7.19)	10.85 (8.89)
Whippen	24.33 (21.28)	11.92 (11.49)
Jack	39.66 (26.93)	16.70 (21.54)
Hammer-butt	45.00 (24.19)	35.08 (21.20)
Hammer	29.25 (18.54)	35.23 (20.41)
Hammer-move	18.25 (16.92)	27.00 (16.70)
Damper-spoon	11.25 (6.62)	4.69 (5.88)
Damper	55.92 (27.33)	62.85 (40.17)
Balance and back-check	63.41 (60.83)	44.69 (29.79)
Synchronized		
Key	12.30 (11.37)	17.14 (17.15)
Whippen	47.84 (37.39)	53.00 (62.26)
Jack	57.53 (43.65)	44.64 (28.74)
Hammer-butt	76.61 (55.92)	48.35 (24.15)
Hammer	50.61 (37.87)	40.64 (15.58)
Hammer-move	27.84 (13.28)	26.80 (15.96)
Damper-spoon	17.00 (14.74)	8.36 (7.90)
Damper	83.92 (58.57)	67.00 (30.87)
Balance and back-check	75.00 (56.11)	40.57 (16.06)

HPS/LTR. A repeated measures ANCOVA, including learning time as continuous covariate factor, synchronization and cue type as between subjects factors and the three aggregated categories as within subjects factor, revealed an effect of learning time on the overall number of fixations, $F(1, 47) = 268.57$, $p < 0.001$, partial $\eta^2 = 0.85$, but no significant difference in the number of fixations in the synchronized and the non-synchronized condition, $F(1, 47) = 2.81$, ns; however, a main effect of AOI category was found, $F(2, 94) = 3.57$, $p = 0.031$, partial $\eta^2 = 0.07$. A marginally significant interaction was found between synchronization, cue type and AOI category, $F(2, 94) = 2.86$, $p = 0.061$, partial $\eta^2 = 0.06$. This marginal interaction showed that in the synchronized condition, the number of fixations was higher for the MPS/HTR and HPS/LTR in the arrow cue condition ($M = 134.15$, $SD = 96.78$ and $M = 237.38$, $SD = 149.82$, respectively) than in the spreading-colour cue condition ($M = 93.00$, $SD = 51.86$ and $M = 167.85$, $SD = 40.73$, respectively), but lower for the LPS/HTR category (for arrow cue condition $M = 76.00$, $SD = 52.40$, and for spreading-colour cue condition $M = 78.50$, $SD = 75.76$, respectively). So, we can conclude that the proportion of fixation in LPS/HTR category was higher for the spreading-colour cue condition than for the arrow condition. The corresponding pattern was not found for the non-synchronized condition. This result parallels that one found in Experiment 1. As in Experiment 1, a significant interaction between AOI category and learning time was found, $F(2, 94) = 16.31$, $p < 0.001$, partial $\eta^2 = 0.26$. The direction of this interaction indicated that the effect of learning time on fixation number was higher for the HPS/LTR and MPS/HTR categories than for the LPS/HTR category. This result suggests again that the effect of the cueing device (in particular spreading-colour cue) influences information processing location early in the study of the animation.

3.2.4. Eye tracking data and comprehension

As in the first experiment, a regression analysis was performed. A general regression model was used, with number of fixations in each of the different AOIs as nine continuous predictor variables, synchronization and cue type as between subjects predictor variables and comprehension measures (configuration, kinematics and functional mental model quality) as dependent measures. This analysis showed significant effects for comprehension regarding the number of fixations on the whippen, $F(3, 33) = 2.99$, $p = 0.04$, partial $\eta^2 = 0.21$, and a nonsignificant effect of the number of fixations on the hammer, $F(3, 33) = 2.43$, $p = 0.082$. This regression pattern approximately paralleled the one found in the first experiment.

3.3. Discussion

Synchronization of suitable cueing with user-control of the piano mechanism animation has a positive effect on comprehension with respect to kinematics and also functional mental model development. This finding indicates that synchronization is crucial to help learners to coordinate spatial and temporal aspects of their visual exploration with the changes in the locus of thematically important content aspects that occur as the animated presentation progresses.

4. General discussion

Our experiments compared two design manipulations for making crucial high relevance aspects of the dynamic information that is available in complex animations more accessible than it would be in a ‘realistic’ depiction. A new type of cue was designed, the spreading-colour cue, which provides specific and continuous spatio-temporal direction of attention by tracing the pathway of important causal chains. The findings from the two studies presented here suggest that this approach can support learners in the first phases of processing of complex animations, more than an arrow cue, provided it is synchronized with key functional events within the animation’s time course. This effect on processing also results in better comprehension. The empirical results from the two experiments are consistent with the largely bottom-up first few stages of the model by Lowe and Boucheix (2008).

To complete this discussion section, we will address a number of questions that arise from our investigations and results that need to be considered further. A first question concerns the design of the arrow cue condition. In contrast to the spreading-colour cue, the arrows did not use different colours to help differentiate key aspects such as the hammer and the damper subsystems. In addition, the implementation of the arrows had them pointing systematically to each local movement of the system’s parts rather than specifically to high relevance locations such as the whippen. This raises the question of what would happen if we were to redesign the arrows so that they pointed to the whippen or other crucial components at the critical time. However, a potential problem with arrows would remain, which is that they are instantaneous across space and time rather than cumulative. Thus, although isolated arrows with different colours that point to crucial parts could in principle distinguish specific locations belonging to either the hammer system *or* the damper system, they would not provide a continuous pathway of explicit spatial and temporal linkage for the locations along the causal chains within each system. In contrast, the progressive form of attentional guidance available with the spreading-colour cue adds “visual coherence” by dynamically linking specific locations.

A second question concerns the potential effect of the inserted “instantaneous cues” used to indicate impact events in the spreading-colour cue condition. It is quite possible that this instantaneous cueing may have produced an effect additional to that of the spreading-colour cue itself. The goal of the novel cueing approach investigated in this research was to provide a comprehensive attention guidance system tailored to suit the specific dynamic content depicted in a given animation. This system was designed to direct attention to functional relations across space and time in order to facilitate learner processing of both distributed sequences of actions (such as the key-to-hammer causal chain) and brief localised events (such as the balance-back-check impact). The encouraging results from this research need to be followed up with studies that tease out the individual contributions of the spreading-colour and instantaneous cueing.

Finally, our results also revealed that in the arrow cue condition, there was no interference from using two very different types of arrows for two distinct aspects of the animation: (a) a large controllable arrow, far from the system itself for key press and release and (b) smaller cueing arrows (synchronized but not controllable) pointing to specific locations near each component. Moreover, a user-control familiarization task involving use of the same type of large controllable arrow to manipulate a simple circle along a line on the computer screen was performed by each participant before the experiment in order to minimise any potential interference.

Because the focus of the present study was upon animation processing *per se*, we did not provide instructional explanations during the animation. However, it is of course possible that animations accompanied by explanations would require less or differently timed guidance from devices such as spreading-colour cues (e.g., synchronization with the explanations). This possibility is another challenging question for future investigation.

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Appendix. Scoring guide for 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.

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