Perceptual processing and the comprehension of relational information in dynamic diagrams

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Abstract. To date, research on the processing involved in comprehending and learning from animated diagrams has accorded a minor role only to perceptual operations in general and peripheral processing in particular. For those aspects where the role of perception is acknowledged, it is foveal rather than peripheral processing that is regarded as the main player. In this paper, we use the results from additional finer grained analysis of data collected in a recent empirical study to suggest that information from a viewer's peripheral field can play a much more central role in animation processing than has previously been recognized. It appears that if the dynamic information comprising an animated diagram is presented in a suitable way, the resources available for visual perception can be partitioned so that responsibility is shared efficiently between foveal and peripheral processing. Implications with regard to elaboration of the Animation Processing Model and possible interventions for improving animation processing are discussed.

Keywords: Animated Diagrams, Peripheral Processing, Relation Formation.

1 Introduction

In this paper, we elaborate some aspects of the five-phase Animation Processing Model (APM) [1; 2], a theoretical framework concerned with the perceptual and cognitive activity involved in comprehending an externally presented animated diagram depicting complex, unfamiliar subject matter. The basic building blocks for this activity are individual event units (where event units are the entities depicted in an animation plus their associated dynamics). Figure 1 summarizes the APM phases involved in building a high quality mental model from an animation by a blend of bottom-up and top-down processes. APM Phase 1 processing involves a viewer's initial parsing to decompose the animated display's continuous flux of information into the separate event units that constitute the raw material for further processing. The APM characterizes this initial decomposition as an essentially bottom-up activity that is based largely on the perceptual attributes of the animated display. The other four phases involve the progressive composition of event units into increasingly inclusive knowledge structures that culminate in a high quality mental model of the depicted subject matter.

Influences	Phase		Activity	Outcome
Top-down influences	5	**Mental model consolidation**	Elaborating system function across varied operational requirements	Flexible high-quality mental model
	4	**Functional differentiation**	Characterization of relational structure in domain-specific terms	Functional episodes
	3	**Global characterization**	Connecting to bridge across 'islands of activity'	Domain-general causal chains
	2	**Regional structure formation**	Relational processing of local segments Into broader structures	Dynamic micro-chunks
Bottom-up influences	1	**Localized perceptual exploration**	Parsing the continuous Flux of dynamic information	Individual event units

Fig. 1. The Animation Processing Model summary diagram

With respect to bottom-up, perceptually-based activity, our initial version of the APM accorded only a minor role to peripheral processing and essential confined its involvement to supporting Phase 1 decomposition. We implied that once event units had been separated out as raw material for mental model construction, the perceptual activity contributing to their subsequent hierarchical composition into causal chains essentially relied on foveal processing alone. For example, this would be the case in APM Phase 2 which involves the primary composition of adjacent event units into small local groups (termed *dynamic micro-chunks*) that are bonded together by domain general relationships, a knowledge of which has been acquired from the viewer's experience of the everyday world and its dynamics. Fundamental to the formation of dynamic micro-chunks are cause-effect relations where there is (i) a directed association between multiple dynamic changes that occur close together in time, and (ii) some type of link that connects these changes.

The elaboration of the APM presented in this paper was prompted by empirical and theoretical work undertaken in the ten years since its original exposition [1]. Although this work initially targeted APM Phase 1 processing (the preliminary decomposition of an animated display), the present contribution relates to subsequent activities in Phases 2 and 3 by which the viewer progressively composes individual event units into higher order knowledge structures. Our particular focus is upon the necessity of effective perceptual processing as a foundation for characterizing key relationships depicted in an animated diagram.

1.1 Composing relations

The APM provides an account of the processing involved in learning from conventionally-designed animations that provide a comprehensive and dynamically faithful representation of their subject matter. From this account we hypothesized that deficiencies in learning from such materials are due to a mismatch between (i) the dominant design approach used to develop conventional animations and (ii) the way learners actually process dynamic representations [2].If this is so, better alignment between animation design and learner processing should improve learning. A novel animation design was therefore devised that departed radically from the standard approach of providing a veridical presentation of the subject matter's dynamics. This alternative 'Composition Approach' [2] provides learners with a contiguous succession of carefully crafted partial (mini) animations designed to facilitate extraction of relevant information and its progressive composition into higher order mental structures. Using the working of a traditional upright piano mechanism as the to-be-learned subject matter (Fig.2.), we employed three experimental conditions to compare the effectiveness of different animation designs(see [3] for experiment details): (i) Comprehensive (conventionally designed, with all components and behaviors included, as per Fig. 2), (ii) Contiguous (a succession of partial animations, each depicting two contacting and directly-relatable components at a time), and (iii) Non-contiguous (a succession of partial animations in which pairs of components were not in contact and therefore not directly relatable) (Fig. 3). The set of partial animations in both the Contiguous and Non-contiguous versions covered all components depicted in the Comprehensive animation.

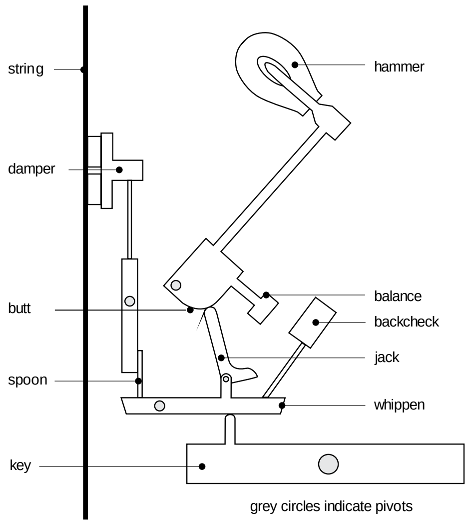

Fig. 2. Traditional piano mechanism. A conventional (Comprehensive) animation presents all these components together and faithfully depicts their dynamics (operational details in [3]).

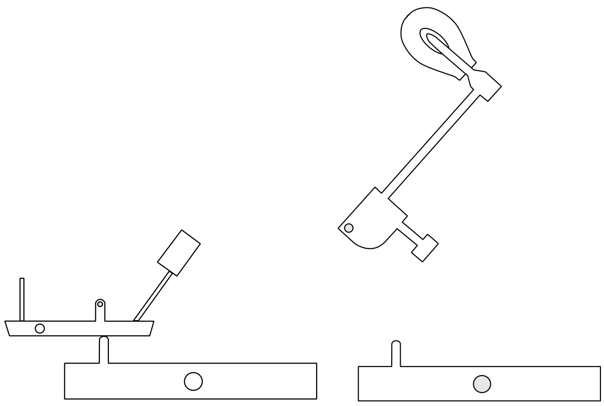

Fig. 3. Example Contiguous (left) and Non-contiguous (right) partial animation frames.

Participants who studied the Contiguous version performed significantly better on a test of mental model quality than those in the Comprehensive and Non-contiguous conditions (Contiguous mental model scores were more than half as large again as scores from the other two conditions) [3]. Eye tracking data were collected using Areas of Interest (AOIs) based on parts of the piano mechanism such that the outline of each AOI captured the region swept out by that component or sub-component during the course of its movement. Figure 4 is a notional depiction that illustrates the principle used to define these AOIs (but in practice, the boundaries of AOIs were extended somewhat to ensure that all relevant fixation data are included). Viewers' foveal fixations on different parts of the display were analyzed in terms of their frequency and duration.

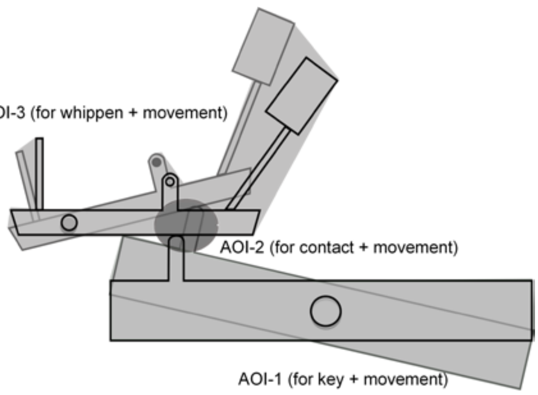

Fig. 4. Grey regions provide a notional illustration of the three AOIs used to capture regions swept out by the key, whippen and key riser contact during operation of the piano mechanism.

Eye tracking data from the experiment revealed an unusual negative correlation (r = -0.81) between number of fixations made and fixation duration. These fewer, longer fixations were interpreted as an indication of deeper processing. Comparison of the eye tracking videos from the three conditions suggested that participants in the Contiguous condition made particularly prolonged fixations in the small regions of contact between pairs of components (e.g., where the key riser contacts the underside of the whippen, see Fig. 4, AOI-2). Statistical analysis of the eye tracking data showed that the total fixation duration on each of these contact regions (key-whippen, whippen-jack, jack-butt, etc. etc.) was significantly greater for Contiguous participants (Table 1a). This contact region is of particular importance with regard to the dynamic relations that occur for component pairs presented in the Contiguous condition because it is the crucial link between a cause and its effect.

Table 1. Part a of this table presents Means (SD) and one way ANOVAs for eye fixation lengths (in seconds) and counts across the total animation exposure time. It reports results from all three conditions (Contiguous, Non-contiguous and Comprehensive, each one N = 20) for (i) contact AOIs in the animation, and (ii) the remaining non-AOI area. Part b of the table concerns just a short subsection of the total exposure time for the Contiguous condition only and compares the Foveal Processing Intensity Indices (see explanation below) for the contact and component AOIs.

Gaze measures	Locations	Contiguous	Non-Contiguous	Comprehensive	ANOVAs
Part a *Total animation exposure:4 minutes* Fixation length	All Contact AOIs	120.02 (18.38)	89.73 (18.55)	103.62 (20.67)	$F(2,57) = 12.49$ $p < .0001$ $\eta p^2 = .30$
	Non AOI area	107.79 (14.35)	133.62 (14.61)	124.50 (19.91)	
	Total	227.81 (15.53)	223.36 (22.52)	228.13 (20.51)	
Fixation count	All Contact AOIs	204.20 (45.03)	196.15 (44.23)	215.40 (61.89)	$F(2,57) = 0.71$ $P = .49$ $\eta p^2 = .02$
	Non AOI area	272.65 (71.03)	364.15 (57.58)	327.85 (51.00)	
	Total	476.85 (107.93)	560.30 (89.39)	543.25 (96.92)	
	Contact AOIs	0.52			
	Component AOIs	0.04			

Unusual clusterings of fixation activity observed in the videos prompted us to single out the set of eye tracking data obtained from those in the Contiguous condition for more in-depth analysis. Of particular interest were activities concerned with the processing of fundamental cause-effect relationships that are central to APM processing phases 2 and 3. According to the APM, the cause-effect relationships a viewer establishes during these phases are domain-general (rather than domain-specific). In order to establish such a relationship between two interacting components of the piano mechanism, the viewer must characterize not only the contact interaction that links the cause and effect components involved, but also the respective dynamics of those two components (refer to Fig. 4).

We therefore expected further analysis of the Contiguous participants' eye tracking data to show that their concentration of foveal processing on this contact interaction region was accompanied by a similarly close monitoring of component movements. If both of these substantial monitoring tasks were being carried out by foveal processing, fixation activity should be appropriately distributed between the contact AOIs and the component AOIs. To test this expectation, we devised an *index of foveal processing intensity* that expressed fixation durations per unit area (calculated as the ratio between the total foveal fixation duration in each AOI (seconds) and the total area of that AOI (cm^2). Fine grained analysis using this index was concentrated on a 20 second segment of the Contiguous animation comprising the movements of the key, whippen and jack. The AOIs on which this analysis was based captured two classes of eye tracking data (i) fixations on the small areas of contact between adjacent components where cause-effect interactions took place (for key-whippen, whippen-jack and jack-butt) and (ii) fixations on the much larger areas swept out by whole components or major subcomponents as they performed their operational movements (the key, whippen, jack, and butt). Results for the index of foveal processing intensity are shown in table 1b.Contrary to our expectations; these results indicated that although participants in the Contiguous condition applied a very high level of foveal processing intensity to the regions of contact interaction, they applied a very low level of such processing activity to the components themselves (Table 1b). Further, almost none of the 20 participants ever fixated on the key or the whippen whereas they all made multiple and prolonged fixations within contact AOIs.

This puzzling apparent neglect of information that is absolutely central to establishing causal relationships left us with the question of how participants could be characterizing the respective behaviors of the cause and effect components, if not via foveal processing. In the next section, we suggest an alternative means by which those in the Contiguous condition may have extracted this vital information. To prepare the ground for explaining our suggestion, we first use a specific example to elucidate the types of dynamics involved when two piano components interact.

2 Partitioned Perceptual Processing

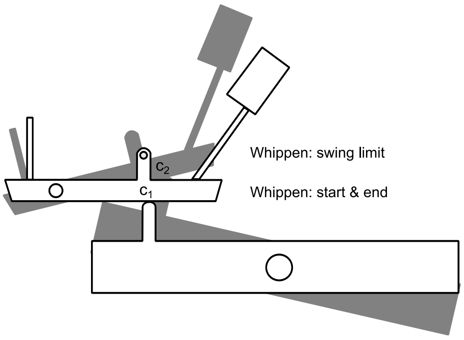

Fig. 4. Example showing (i) global cause and effect movements of a pair of piano components and (ii) the local contact interaction that links these together into a causal relationship.

Figure 4 depicts a subset of the piano mechanism that consists of just the key and the whippen. These two components are in contact at the point where the key's riser meets the whippen's lower surface. Before a piano player depresses the key, this point of contact is located at position C_1. Then when the key is played, it rotates clockwise around its pivot and the riser protruding from its top surface pushes on the whippen. This interaction causes the whippen to rotate anticlockwise around its pivot until the key and whippen both reach the limit of their respective swings. By that moment, the key-whippen contact has reached position C_2. Then upon release of the key, its riser retraces its journey back to C_1 along the undersurface of the whippen as these components return to their starting positions.

Two very different types of movements are present in this complete cycle. On one hand, there are the macro-scale reciprocal swings of the key (clockwise) and the whippen (anticlockwise). This movement patterns exemplifies a very common type of see-saw behavior exhibited by many everyday devices involving simple levers consisting of a rigid bar that is free to rotate about a pivot. Our extensive experience with such devices equips us with well-developed domain general background knowledge about their typical behavior. On the other hand, the riser-whippen contact interaction that takes place to-and-fro along the path between C_1 and C_2 occurs on a far more restricted (micro) scale. The exhibited behavior is also highly specific to this particular case of the piano mechanism and therefore not underpinned by the type of domain general knowledge that is available for the macro-scale reciprocal swings of the key and whippen.

We suggest that the extreme differences in these two aspects of the dynamics likely have important implications for viewers' allocation of perceptual resources when they process such pairs of interacting components. Our assumption is that in order to comprehend the role that this type of interaction plays in the piano mechanism's overall functionality, viewers need to be able to comprehensively characterize the cause-effect linkage involved. This requires them to relate (i) the micro-scale details of the continuous contact interaction along the C_1 - C_2 pathway to (ii) the macro-scale reciprocal swings of the key and whippen that occur during this interaction. A parsimonious way to perceive the information required for establishing this relationship internally would be to process these two aspects of the dynamics in parallel.

Human visual perception in general relies on the complementary, coordinated operation of foveal and peripheral processing [4]. Perception can be optimized by appropriately partitioning these perceptual resources between the various aspects of a set of visual information that confronts the viewer. With regard to the present key-whippen example, we contend that foveal processing should be better suited to the more detailed analysis required for characterizing micro-level information about the riser-whippen contact interactions, while peripheral processing should be better suited to dealing with the macro-level information concerning the overall reciprocal motion of the key and whippen. Such matching of processing type to processing task can be thought of as a form of perceptual partitioning. If this type of perceptual partitioning does indeed occur, eye tracking data should indicate that viewers tend to allocate most of their foveal processing resources to the small region in which contact interactions occur, while leaving peripheral processing to take care of the more global movements of the key and whippen.

3 Elaborating the APM and improving effectiveness

The preceding discussion raises the possibility that peripheral processing can play a far more central role in comprehension of animated diagrams than previously acknowledged. Our empirical results reported above support this possibility. The almost total neglect of peripheral processing in research on learning from animation can perhaps be attributed to influences such as the dominance of eye tracking approaches in this field(a technique based on foveal processing only) and the widespread view that peripheral processing is intrinsically ‘inferior’ to its foveal counterpart, a notion that has been contradicted by recent research. [4]. It may well be time to confront these influences and redress the limiting effects they could have on future progress of animation research. This would require researchers to no longer ignore the possibility that information acquired via peripheral vision may make a substantial and ongoing contribution to animation processing (c.f. [5]).

However, it is important to note that the phenomenon of perceptual partitioning reported in this paper came to light under the very particular circumstances that existed in the Contiguous animation condition (which produced the best mental models). Those circumstances allowed Contiguous participants to devote their foveal processing capacity almost exclusively to the demanding task of analyzing and characterizing details of a contact interaction linking cause to effect. In parallel with this all-consuming foveal activity, they were also able to monitor associated changes of the cause and effect components by delegating such monitoring to peripheral processing. A far less satisfactory alternative scenario for Contiguous participants based on foveal processing alone would have been for them to make multiple fixation switches between highly localized contact interaction dynamics and more global component dynamics (c.f. [6]). In addition to being a much less parsimonious use of processing resources, such an alternative would carry the risk of various disruptions involved in switching between different sites of activity.

Nevertheless, such a partitioning between foveal and peripheral processing that enables them to operate in parallel is in fact a normal (rather than exceptional) feature of everyday vision [4], especially in dynamic situations. For example, in situations such as car driving, an individual can automatically monitor a vehicle's wider dynamic surrounds while at the same time performing detailed, analytical visual interrogation of far more localized information [7]. However, this efficient and highly successful form of resource allocation can of course be severely compromised by misallocation of foveal processing (such as viewing a mobile phone screen during driving) and the serious disruptions that switching between different visual targets typically involves.

The 'ideal' processing situation that appeared to pertain for participants who studied the Contiguous version could also be compromised by introducing changes likely to degrade peripheral processing. One way to introduce such change would be to add more information to the surroundings of each of the component pairs used in the Contiguous condition (for example, by including more of the piano's mechanism in these partial animations).Addition of such 'clutter' introduces visual crowding that can have a negative effect on the scope, accuracy and coherence of information extraction via peripheral processing [4]. This may partly explain why the results obtained by animation researchers (who almost exclusively use cluttered conventional comprehensive animations in their investigations) have not alerted them to the possible role of peripheral processing that has been indicated by our present findings.

3.1 Elaborating APM stages 2 and 3

While acknowledging the caveats given above, it seems prudent to review several aspects of the APM (as outlined in its original exposition) to take account of the findings presented in this paper. In the initial version of the APM, it was suggested that once the continuous flux of a presented animation had been decomposed into individual event units during Phase 1, Phase 2 processing could proceed during which the viewer connects two *or more* event units at a time into superordinate composite structures that we termed 'dynamic micro chunks'. However, if a viewer is able to invoke the form of partitioned perception discussed in this paper, it would presumably be best to process event units in pairs, rather than in larger groups. Pairwise processing should allow a highly efficient allocation of perceptual resources in which there is a near optimal match between (i) the processing aspect that is engaged (foveal or peripheral) and (ii) the task to which that aspect is applied (detailed analysis of contact interaction or global characterization of cause-effect dynamics). The efficacy of dealing with dynamic targets in a pairwise fashion has been clearly demonstrated in research with air traffic controllers [8].

With respect to Phase 3 processing, the initial version of the APM is somewhat lacking in processing detail about just how the dynamic micro chunks formed during Phase 2 become connected up by bridging relations to form a superordinate structure of causal chains. A pairwise approach similar to that posited for Phase 2 also seems applicable to Phase 3 since it could be based on the same type of perceptual partitioning. To make this more concrete, consider two possible combinations of event units that could be formed during Phase 2 processing of a conventionally designed (comprehensive) piano animation: (i) a key-whippen dynamic micro chunk and (ii) a jack-hammer micro chunk. The linking up of these two chunks as part of a causal chain is via the pivot that attaches the base of the jack to the riser of the whippen. In terms of the perceptual partitioning approach, the task of characterizing what happens in this highly localized site would be allocated to foveal processing. The detailed analysis occurring in this small region would be complemented by peripheral processing of the dynamics of the proximal whippen (cause) and the jack (effect) rather than the dynamics of the more distant hammer and key (Fig. 5). Note that Figure 5 is merely a stylized conceptual representation of this possibility; in reality, there would be gradual degradation of the peripheral information with distance from the centre, rather than the sudden change depicted here.

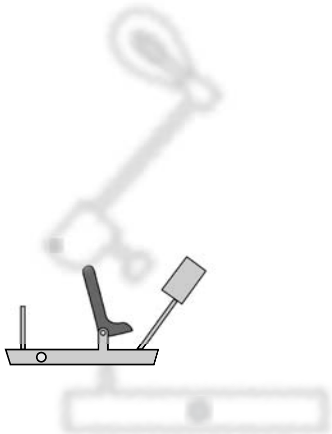

Fig. 5. Hypothetical situation in which perceptual partitioning could be invoked (conceptual representation only). Partitioning is confined to peripheral field closest to contact interaction.

The elaborations of APM phases 2 and 3 suggested in the foregoing discussion have been considered only from the perspective of the role that perceptual partitioning could play in the progressive composition of individual event units into domain general causal chains. However, this perceptually-oriented account should be complemented by a consideration of how contributions from top-down processing could modulate the apportioning of perceptual processing discussed earlier. For example, in the case of the piano animation, it is highly improbable that a top-flight piano repair technician (i.e., someone with domain specific expertise in the animation's subject matter) would follow the same processing route during viewing as those who lack specialist knowledge in this domain. Instead, the technician's focus is likely to be on the finer points of piano functioning (rather than its basic operation), with foveal processing used extensively to interrogate these aspects of the mechanism's dynamics.

3.2 Intervening to improve conventionally designed animations

Researchers have considered a variety of factors that may influence comprehension of animations [9], ranging from the dynamic spatial ability of the viewer [10] to the forms of support that are provided to accompany presentation of an animation [11]. Most interventions intended to improve animation processing have, at best, met with limited success. However, it is possible that the phenomenon of perceptual partitioning may provide a more promising basis for devising supportive interventions, not the least because it appears to be theoretically robust and is derived from empirical evidence.

Pronounced partitioning of perceptual resources by which foveal and peripheral processing were optimally allocated to local and global aspects of cause-effect relation formation occurred only for participants who studied the contiguous version of the animation. However, because the design of this version according to the Composition Approach involves a radical departure from the currently prevailing entrenched design orthodoxies, this strategy for improving effectiveness is something not likely to be widely adopted by animation designers in the near future. This raises the question of whether or not it would instead be possible to devise other ways of obtaining the processing efficiencies afforded in the contiguous condition but with a conventional comprehensive animation design rather than one designed according to the-Composition Approach.

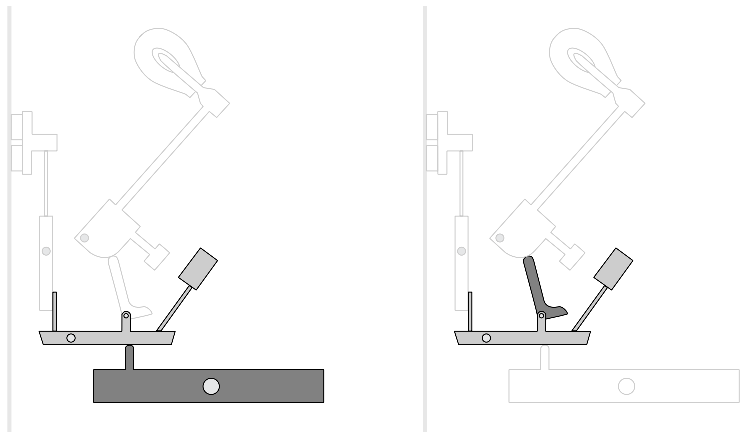

Fig. 6. Possible use of anti-cueing to produce a situation resembling that available in a Composition Approach (i.e., Contiguous pairs) but with a conventionally designed animation.

One possibility could be to approximate the type of situation that exists with a contiguous version pair by applying a suitable intervention to an existing conventionally designed comprehensive animation. If we consider a comprehensive animation of the piano mechanism as an example, perhaps the desired processing affordances could be obtained by ‘visually suppressing’ all parts of the mechanism except for a pair of event units (e.g., the key and whippen) using anti-cueing techniques such as fading (Fig. 6). Changing the region across which this anti-cued is applied in a stepwise fashion over time should produce a situation that presents a succession of pair-wise processing opportunities resembling those that were provided in the Contiguous condition. Empirical research is needed to investigate this and other intervention strategies that have the potential to stimulate beneficial perceptual partitioning.

4 Discussion and conclusion

Our motivation for updating the APM in light of recent empirical and theoretical work is a continuing quest to develop a principled basis for redressing the mismatches between design features and human information processing that exist with conventional animations. Effective extraction from an animated diagram of information about dynamics plays a crucial role in building a high quality mental model of the depicted subject matter because this behaviour indicates the causality that underpins the operation of a system. One feature of research into animation processing to date has been the relative neglect of perception (compared with cognition). This is a considerably more important issue for dynamic displays like animated diagrams than it is for static diagrams because of the powerful influence that dynamics have on perception (and hence information extraction).

We were initially alerted to the possibility of a previously unreported type of perceptual processing by unexpected patterns of fixation in eye tracking videos from a recent experiment. Empirical evidence subsequently gathered from further analysis of the eye tracking data suggested that not only foveal but also peripheral perception can be important in processing animated diagrams efficiently and effectively. For the Contiguous paired presentation, this evidence indicated that, in essence, foveal processing was being devoted exclusively to close monitoring of contact interaction between the components in a pair leaving the task of characterizing the associated overall movement patterns of those components to peripheral processing. More specifically, available perceptual resources were being allocated in parallel according to individual task requirements: detailed analysis of micro-scale dynamics to foveal processing and broad characterization of highly familiar everyday macro-scale dynamics to peripheral vision. Despite the findings being highly novel (and unexpected), this form of tailored resource allocation is not in fact exceptional but rather perfectly normal in everyday visual perception. The findings are also highly consistent with a central aspect of the APM: the composition of event units into more inclusive knowledge structures.

The likely implications for elaborating the APM are that (i) perceptual processing plays crucial role not only in extracting individual event units from an animation’s dynamic flux (Phase 1) but also in contributing to the composition of these basic building blocks into higher order information structures such as causal chains (Phases 2 and 3), and that (ii) considerable benefits can be achieved by fostering perceptual partitioning in which responsibility is shared between foveal and peripheral processing resources. However, it appears that for such partitioning is contingent on the dynamic subject matter being offered in a suitable fashion (in the case considered here, this was according to the specific pairwise presentation regime available in the Contiguous condition).

The Contiguous animation discussed in this paper was devised primarily for research purposes. Despite its effectiveness, we did not intend it to be adopted 'as-is' by practicing animation designers. Rather, we acknowledge the reality that conventional approaches to designing animations will continue to be dominant into the foreseeable future. However, the situation that exists in unsupported Comprehensive animations is the antithesis of what is required to allow highly efficient partitioning of perceptual resources. For this reason, we are interested not only in using our findings to elaborate the APM, but also in using the insights gained to suggest related interventions (such as the use of anti-cueing to support pairwise processing) that may improve the effectiveness of comprehensive animations. It would also be important to empirically test the effectiveness of using anti-cueing with comprehensive animations (as proposed in this paper) to simulate the type of pairwise processing situation found in the Contiguous condition. The perceptual partitioning finding appears likely to be generalizable to animations of many other mechanical systems that are based on similar types of cause-effect relationships (such as the toilet cistern studied by Hegarty and colleagues [12]). However, this possibility needs to be investigated by future empirical research.

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