Creating Perceptually Salient Animated Displays of Spatiotemporal Coordination in Events

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Abstract Geographic phenomena exist within a multi-dimensional space–time continuum. Dynamic geographic phenomena at all levels of scale can be conceptualized and represented as spatiotemporal patterns, space–time processes, or events—changes within or between objects that are experienced as bounded by psychologically discreet beginnings and ends. Humans rarely care about spatiotemporal entities in isolation. Visualization and analysis approaches that focus on individual spatiotemporal phenomena in isolation are likely doomed to failure because they miss the relational structure humans use to process and reason about events. We contend that a static and geometric decompositional approach to spatiotemporal patterns and processes limits the tools that can be applied to a broad class of spatiotemporal data that are important to users. This class includes events where there is a spatiotemporal coordination among or within objects, such as a car changing its movement direction because of an approaching car, or a hurricane not making landfall because of changing atmospheric conditions. Often such coordination allows inferences about causal relations among the components of an event. In this chapter we argue for the need for perceptually salient and cognitively inspired animated displays that help humans more effectively and efficiently detect relationships in complex events.

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1 Introduction

Dynamic geographic phenomena can be generally conceptualized and represented as spatiotemporal patterns (e.g., trajectories of people or animals, flows of chemicals, or movements of eyes over maps), space–time processes (climate change, urban growth, human spatial cognition), or events (discrete changes over time e.g., earthquakes, Winter Olympics, or human eyes fixating on a perceptually salient object in a scene). Here we use the term *event* to refer to changes over time that are discretized by the observer and are defined as "a segment of time at a given location that is conceived by an observer to have a beginning and an end" (Zacks and Tversky 2001 page 3; for further elboration see e.g. Kurby and Zacks 2008). Events are mental units and are considered as our building blocks of the temporal realm (Schwan and Garsoffky 2008; Shipley 2008). There may be an objective basis for the psychological boundaries in time in an event. For example, an earthquake begins when the ground begins moving and ends when the movement ends. However, there is not always a clear objective beginning or end to a psychological event. For example, does *a wedding* begin when the first guest arrives, or when the bride enters the church—there is no defining moment of wedding onset in the flurry of nuptial activities, yet humans treat the event as well bounded in space and time. Note, events are not necessarily brief abrupt changes; events may be spread out over time, such as a war, or an ice age.

With increasing interest in and use of animations to present and explore complex spatiotemporal data, the research community has developed highly sophisticated visual analytic tools to analyze spatiotemporal patterns for experts and impressive animation tools to present spatiotemporal data to a broader audience (Andrienko et al. 2008, 2010). Animations of spatiotemporal phenomena have been widely used to try to reveal and understand environmental processes and the relations between changing objects (Harrower 2004; Dorling and Openshaw 1992). Cartographic animations include the visualization of events in chronological order e.g., diffusion processes of diseases, human migration, or traffic simulations (Harrower and Fabrikant 2008). In each case, structure or regularities that exist over time might be invisible, or at best obscure, in static snapshots. As these tools develop it will be important to specifically consider research on the information that users can get from animations (e.g., Lowe and Schnotz 2008), as the perceptual and cognitive systems of the users will determine the salience of the patterns and ultimately how effective users will be in detecting and reasoning about spatiotemporal patterns.

Users are often unreliable in their estimates of the quality of information they can get out of animations, and in judging the best visualizations for extracting specific information (e.g., Hegarty and Kriz 2008; Hegarty et al. 2009). Here we consider two aspects of animation design, the number and spacing of moving elements, that influence what can be seen in motion displays. Basic movement properties (Dodge et al. 2008) are not always clearly visible to the viewer in displays with multiple motions due to masking of one motion by another. Furthermore, in cluttered animations attention problems can arise due to limits imposed by the cognitive load of keeping track of multiple variables (Harrower 2007) or by perceptual bottlenecks (Fabrikant and Goldsberry 2005). The result is that it can be hard to extract information about the motion of one or a few points due to other motions. It should be noted that broad arguments about failures of animations are at present limited by the relatively narrow set of domains in which research has been conducted. Many of the studies on animation conducted by cognitive scientists focused on mechanical systems, or processes with real, observable movement of objects that are constrained by physical properties (e.g., moving parts of complex mechanical systems). These studies have not yet addressed the relative efficiency of static and animated displays for geographic visualization of abstract, non-tangible dynamic processes represented in maps (e.g., diffusion, tectonic subduction, meteorological changes, etc.). While Tversky and colleagues have written extensively about the lack of benefit of animations over static depictions of space–time phenomena (e.g., Tversky et al. 2002), there is still an open question, is the failure of animations to live up to their expected potential an inherent problem with presenting information over time, or simply a consequence of poor choices in the design of most animations (Fabrikant et al. 2008a)? With the development of visual analytic tools it will be important to consider research on the information that users can get from animations (e.g., Lowe and Schnotz 2008), as the perceptual and cognitive systems of the users will determine the salience of the patterns and ultimately how effective the user can detect and reason about spatiotemporal patterns.

2 Our Perspective

2.1 Thoughts on Animations

Lowe's (1999) research on complex interactive weather map animations is often cited as an example where animations fail. However, one of Lowe's (1999) research findings was that participants tended to extract information based on perceptual salience rather than thematic relevance. Lowe (1999) offered several reasons why the animations might have failed, including, participants' lack of relevant domain expertise, the complexity of the depicted system, and more importantly the manner in which the system was depicted. So, rather than animations being inherently problematical, one should focus on interactions between the design characteristics and user characteristics.

Cartographers have proposed design principles for animated maps, but rarely, if at all, have these proposals been experimentally tested. DiBiase et al. (1992) suggest that Bertin's (Bertin 1983) visual variables, and later extensions proposed by Morrison (1974) for static maps, are applicable to map animations, such as the addition of color saturation, pattern, crispness, resolution, transparency and arrangement. MacEachren (1995) and DiBiase et al. (1991, 1992) demonstrate the successful implementation of Bertin's variables in map animations in educational material. DiBiase et al. (1992) and MacEachren (1995) further suggest additional design variables specifically for the display of spatiotemporal geographic phenomena. The six variables are: (1) display moment or display date/time (e.g., when in a display does an event become visible), (2) scene duration (e.g., how long a scene is displayed), (3) scene frequency (e.g., frame rate per second, or how fast graphic frames follow one another), (4) scene order (e.g., sequence in which graphics are displayed), (5) rate of change between scenes (e.g., the magnitude of change visible between two sequentially displayed scenes), and (6) synchronization (e.g., the juxtaposition of two concurrent events in the same display). Except for synchronization all six variables have been evaluated, but only in an exploratory and qualitative fashion (Köbben and Yaman 1996). In Blok's (2000, page 18) words: "Synchronization is the possibility to run two (or more) temporal animations simultaneously, and shift them in time so that patterns are in phase, and relationships between data sets can be discovered (e.g., the pattern between emission levels of pollution and the occurrence of certain diseases may be similar, but may only become clear if the time lag has been removed). The question arises whether synchronization can be seen as a variable." We would argue that of these variables synchronization is a critical area for attention as it captures a psychologically critical aspect of events, namely the temporal relationship among changing elements.

2.2 Thoughts on Perception of Movement

In this chapter we argue that research on visualizations should work to develop techniques for presenting and highlighting spatiotemporal relations, because relations are the focus of human perceptual processes. The Gestalt psychologists first made an argument for the centrality of relations (Kohler 1947) and the principle has been embraced by all modern approaches to visual perception.

First, consider two classic examples, the perception of shape and the perception of apparent motion (the appearance of motion when images of stationary objects are presented in rapid succession and thus are seen to move). Object shape is perceived based on relationships within the contours or parts of an object. For example, a triangle may be defined by just three points—one at each vertex. Three non-collinear dots are sufficient to see a triangle, but remove one dot and the viewer is not left with two-thirds of a triangle. There is an emergent property, triangular shape, only visible when three elements (dots) are present; this observation was key to the Gestalt psychologists' argument that human perception could not be understood by accumulation of aspects of individual elements. A similar analysis applies to the appearance of motion in movies. There is no motion evident in any single frame; the motion is only evident by virtue of the relationship between locations of objects and the time between their appearance and disappearance from one frame to the next.

Lest the reader think that this idea is restricted to the highly simplified cases of triangles made of dots and frame-flip animations, we offer a common experience that reveals the deeply relational nature of perception and will perhaps serve to give pause to reductionist inclinations. Imagine a pigeon walking along the ground. Most people will report the pigeon to appear to be moving its head back and forth as it walks (this will be true whether you imagine the scene or you stop reading this chapter and find a walking pigeon). The actual movement of the pigeon's head relative to the environment is an alternation of quick forward movements followed by relative stability, as the body of the pigeon moves forward. This pattern of movement provides the pigeon a stable platform for vision with a relatively short period of time when the movement of the eye would make detection of a moving predator difficult. Why does the pigeon appear to move its head forwards and backwards? Because the movement of the head is not perceived in isolation. All things are seen to move relative to other things. In the case of the pigeon the likely explanation is that the visual system extracts the common forward motion of all of the parts of a pigeon. This common motion is seen as the movement of the object, relative to the larger environment. The local motions of the pieces are then seen in relation to each other. Here the common vector of the forward motion is removed from the local motion vectors and thus the head appears to move back and forth—as it does, relative to the body, but not relative to the larger environment (Johansson 1973).

Humans rarely care about any elemental feature of a scene in isolation. Thus approaches to information displays that focus on individual elements are likely doomed to failure because they miss the relational structure humans use to behave. This idea may be counter intuitive and thus counter to a scientist's natural inclination to analyze and decompose a complex phenomenon into its elements.

2.3 Thoughts on Visualizations

Only a few researchers have looked specifically at modeling and visualizing relationships of spatiotemporal coordination within events (Laube et al. 2005; Andrienko and Andrienko 2007; Stewart and Yuan 2008), and even fewer have done so using animated displays to depict spatiotemporal information in a perceptually salient and cognitively inspired manner (Fabrikant and Goldsbery 2005; Griffin et al. 2006; Klippel and Li 2009). Visualization analyses that consider spatiotemporal information often collapse location information over time to highlight path relationships (Laube et al. 2005). For example, data on the locations of animals over time may be used to analyze how they move through a landscape. Such relationships are analogous to shape relationships, as many of the geometric properties that are important for perceptual processing of static shapes are also relevant for perception of paths (Shipley and Maguire 2008; Maguire et al. 2011).

Analyses that collapse time, however, obscure another important class of relations, temporal relationships among objects. By collapsing across time it is hard to see relationships among object movements. For example, the relationship between predator movements and prey movements would be lost when time is collapsed (indeed it would be hard to distinguish the chaser from the chased). At a larger scale plotting the location over a year of a Sooty Shearwater would make visible an incredible flight path from Chile to Alaska, but the relationship between time of year, or weather patterns, and migration would be lost. The perceptual system is designed to extract relational information because such information allows smooth coordination with ongoing events. The spatiotemporal dependencies among the parts of an event (for example moving objects) can reveal something of the event's dynamics. Understanding the dynamics can in turn allow predictions about what actions will influence ongoing events.

Shipley and Zacks (2008) describe events as things that happen with a reference to a location in time. Events are mental units and are considered as our building blocks of the temporal realm (Schwan and Garsoffky 2008; Shipley 2008). Although events often involve motion, their unitary nature allow analogies to be drawn between events and objects (Casati and Varzi 2008; Schwartz 2008; Shipley 2008; Shipley and Maguire 2008). While objects belong to the spatial dimension without a temporal frame of reference, events are set in the temporal dimension (Casati and Varzi 2008; Shipley 2008; Tversky et al. 2008) and occur when objects change or interact (Shipley 2008). The challenge from the perspective of creating visualizations is knowing how to convey information about temporal interactions. Here the key is to make salient a spatiotemporal relationship among elements. Below we briefly review two cases from event perception research that indicates the visual system picks up patterns that are defined by temporal relations among objects—action recognition and perception of causality. These cases make it clear that users can readily pick up some very complex inter-element coordination. A critical research goal in this area should be to understand what makes certain spatiotemporal patterns salient.

In perception research, one of the most carefully studied cases where the visual system combines information across multiple elements is the case of biological motion perception in point-light displays. For this research human action is reduced to thirteen points, one for each of the major joints on the body—head, wrists, elbows, shoulders, hips, knees, and ankles. In isolation each element's motion appears complex but not human-like (it may look, for example, like a fly buzzing around). When animated together the motions of these points reveal a human acting. These animations can reveal complex aspects of the events, including the gender of the actor, and even the weight of an invisible object from the lifting motion (Koslowski and Cutting 1977; Runeson and Frykholm 1981).

Extracting information about action requires all (or most) of the joints to be visible. A single point's motion is insufficient to reveal the whole action.

Some readers may be familiar with work by Troje (e.g., Troje and Westhoff 2006) who has shown that observers can detect the presence of an animate being from the motion of a single dot tracing the path of a foot. This is not a counter example to our argument. Troje and Westhoff (2006) have argued that this phenomenon represents a low-level pre-attentive visual process that detects the presence of an animate being. This process appears to act something like an accumulator and detects the shape of the motion path. The process can detect a foot moving, but not identify action, which is evident only in the relations among parts of the body.

The basis for recognition of events in such displays appears to be an ability to extract information about the event dynamics, i.e. the forces acting on the bodies in the scene. The spatial structure of the objects is less important than the coordinated acceleration pattern that defines such forces (Troje 2002; Shipley 2003). Analogously, an analysis of motion paths may allow detection of basic event properties but not allow a more sophisticated understanding of interactions among objects evident in higher order spatiotemporal regularities. Indeed subjects find it hard to align static snap shots of an event to a depiction that includes the event dynamics (Lowe et al. 2011).

The visual processing of spatiotemporal coordination of elements in events is not restricted to human action, humans also perceive more complex categorical features of events such as cause (Michotte 1963), and social interactions, like chasing and following (Heider and Simmel 1944). Although the processing of basic physical and social motion patterns may be near universal, even more complex dependencies may be picked up with experience. For example, professional European-football players can recognize patterns of movements based on plays where novices are much less accurate (North et al. 2009). Skill in detecting higher order spatiotemporal regularities may be acquired through a type of perceptual learning where repeated exposure to a complex spatiotemporal pattern allows the visual system to extract parts of the pattern that spatially or temporally predict other parts (e.g., Aslin et al. 1998). Although such learning can occur without direct instruction, guiding an observer's attention to the regularities will likely facilitate learning. We contend that a static and geometric decompositional approach to spatiotemporal patterns and processes will limit development of tools that can be applied to a broad class of spatiotemporal data, or events, that are important to users.

3 Implications for Animation Design

Cartographers generally choose appropriate visual variables to make thematically relevant information perceptually salient, to align with the theme of the map, to fit the purpose of the map and its usage context, and to fit the audience (Dent 1999).

There is an open question as to whether controlled changes in an animation design, i.e., making the thematically relevant information perceptually salient through (carto)graphic design principles can overcome the observed drawbacks of animation discussed above (Fabrikant and Goldsberry 2005; Harrower and Fabrikant 2008). Recent empirical findings from eye-movement experiments provide support for the contention that generally, static small-multiple displays (for example, where multiple graphics that depict variations in different quantities for the same time period are grouped together) cannot be computationally and informationally equivalent to non-interactive animations (Fabrikant et al. 2008a). Here *informationally equivalent* means that any information (value or relationship between values) encoded in one type of display can be found or inferred in the other, and *computationally equivalent* means that any inference from information in one display can be made with equivalent ease by the user in the other display. Simply put, due to differences in the way humans process static displays and animated displays equal information is not equally easy to use to make inferences, and making displays equivalently easy to use might require adding information to one or the other display type.

Despite claims about animation failures, the computational and informational properties of displays (Larkin and Simon 1987) depend on the task, the information extraction goal, and the decision-making context (Fabrikant et al. 2008a). Eye-movement studies have shown that animation design principles can alter people's viewing behavior (Fabrikant and Goldsberry 2005; Fabrikant et al. 2008b). The ease of extracting information from an animation (as evidenced by eye movement behavior) is influenced by the subject's task (i.e., simple or complex tasks) and display design (i.e., interactivity, animation speed, or tweening). Fabrikant and colleagues have suggested, based on preliminary results from a series of experiments on animations (Fabrikant et al. 2008b), that static and animated displays cannot be informationally and computationally equivalent at the same time (Fabrikant et al. 2008a). They found that participants ran interactive animations at significantly higher speeds in a tweened condition (Fabrikant et al. 2008b). This might mean that tweening, which allows the user to more easily track the change of specific elements or features helps people detect small changes because they can be anticipated. Successful anticipation in turn allows participants to run the animation at higher speeds, and to take advantage of visually continuous motion paths for more efficient change detection. They also found that even though participants had a choice to run the animation forward and backward in the interactive map animation condition (to make the interactive animation computationally equivalent to a static small multiple display), they chose to run the animation significantly more often forward than backwards. In other words, just providing interaction mechanisms (i.e., a backward animation function) does not automatically mean that users will employ them, even though this function might help them to make better and faster inferences.

Generally humans orient toward regions of visual discontinuity. Thus, if a critical relationship in an animation is known and the designer has the intent of focusing the users' attention on that relationship, then elements of the relationship could be conveyed in such a way that they appear discontinuous from the background. This could be achieved by signaling the information with luminance transients (dots or regions changing brightness, e.g., blinking on and off), or velocity discontinuities (e.g., a region in a field of uniformly moving elements where some elements are moving in a different direction). Alternatively, if the designer does not want to commit to a particular relationship, they should work to avoid having the viewer distracted by transients that could occur with abrupt changes in luminance, motion, or element density. Here tweening could help avoid confusing velocity signals.

There is a context dependent trade-off that a display designer has to make. If an animation is interactive then it will be necessary to either add additional information between frames, or estimate using interpolation (tweening) between map frames, to avoid attentional blindness effects. On the other hand, if a non-interactive animation is used, then informational content (relative to static small multiples) must be reduced as well. Here simplifying the data might involve depicting less complex individual map frames (i.e., reducing the numbers of classes) in the animation, or reducing the animation speed, to avoid cognitive overload—as has been suggested by Harrower (2003, 2007). The efficiency with which the observer can extract information from displays differs for different types of displays. Sound space–time visualization requires a cognitive conceptual framework for animation development (Lautenschütz 2011). Generally, understanding how humans process spatiotemporal data must be a part of the development of a GIScience of spatiotemporal visualizations.

Understanding users' cognitive limitations and strengths should help to establish "best practices" for display solutions and guides researchers to consider how to better design visual analytics displays of spatiotemporal data. In turn, empirically validating design choices for animations may lead to an enhanced understanding of when animations work to convey information and which factors are important to understand movement.

4 Conclusion

In sum, we suggest that analyzing space–time phenomena in a reductive, decompositional, fashion and focusing on geometrical analyses of patterns in isolation will limit users' understanding of dynamic environmental phenomena and processes. Animations used to represent and analyze space–time phenomena have arguably not lived up to early expectations, however, good animation design principles are not yet established. Animation design principles must provide guidance for both the properties of an individual element over time, and the spatial and temporal context. Furthermore, the user must also be considered. Their expertise and familiarity with complex spatiotemporal patterns will influence how they process animations, and their specific task will also guide attention to specific spatial and spatiotemporal locations. We conclude that an approach to visualizing spatiotemporal patterns and processes requires a solid consideration of the perceptual and cognitive processes of the user to develop tools that can be applied to a broad class of spatiotemporal data.

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