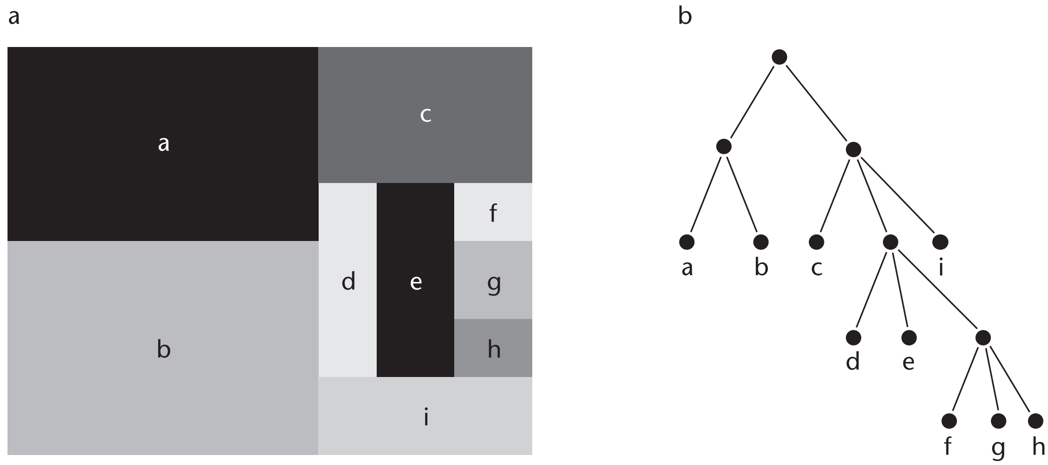

Figure 6.35 (a) A treemap representation of hierarchical data. Areas represent the amount of data stored in parts of the tree data structure. (b) The same tree structure, represented using a node–link diagram.

The original treemap was based on the following algorithm. First the rectangle is divided with a vertical partition according to the number of branches from the root of the tree. Next, each subrectangle is similarly divided, but with horizontal partitions. This process is repeated to the "leaves" of the tree. The area of each leaf on the tree corresponds to the amount of information that is stored there.

The great advantage of the treemap over conventional tree views is that the amount of information on each branch of the tree can be easily visualized. Because the method is space-filling, it can show quite large trees containing thousands of branches. The disadvantage is that the hierarchical structure is not as clear as it is in a more conventional tree drawing, which is a specialized form of node–link diagram.

Patterns in Motion

To this point, we have mainly discussed the use of static patterns to represent data, even though the data is sometimes dynamic—as in the case of a vector field representing a pattern of moving liquid or moving gas. We can also use motion as a display technique to represent data that is either static or dynamic. The perception of dynamic patterns is not understood as well as the perception of static patterns. But we are very sensitive to patterns in motion and, if we can learn to use motion effectively, it may be a good way to display certain aspects of data.

We start by considering the problem of how to represent data communications with computer animation. One way of doing this is to use a graphical object to represent each packet of information and then to animate that package from the information source to its destination.

First we consider the simplest case—data represented by a series of identical and equally spaced graphical elements, as shown in Figure 6.36. In this case, there is a fundamental limitation on the throughput that can be represented. In a computer animation sequence, the basic process is a loop that involves drawing the animated object, displaying it, moving it, and then redrawing it. When this cycle is repeated fast enough, a sequence of static pictures is seen as a smoothly moving image. The limitation on perceived data throughput arises from the amount that a given object can be moved before it becomes confused with another object in the next frame—this is called the *correspondence problem*.

If we define the distance between pattern elements as λ, we are limited to a maximum displacement of $\lambda/2$ on each frame of animation before the pattern is more likely to be seen as moving in the reverse direction from that desired. The problem is illustrated in Figure 6.36(a).

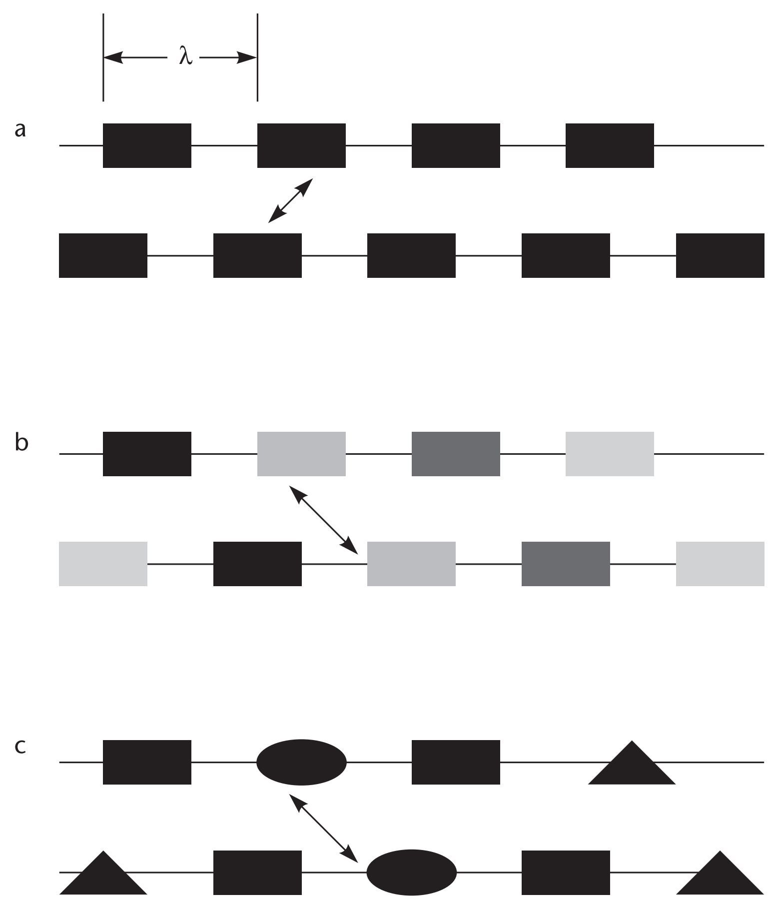

Figure 6.36 If motion is represented using a regular sequence of identical and equally spaced elements, there is a strict limit on the throughput that can be perceived. This limit can be extended by varying the sizes and shapes of the graphical elements.

When all the elements are identical, the brain constructs correspondences based on object proximity in successive frames. This is sometimes called the *wagon-wheel effect*, because of the tendency of wagon wheels in Western movies to appear to be rotating in the wrong direction. Experiments by Fleet (1998) suggest that the maximum change per frame of animation for motion to reliably be seen in a particular direction is about $\lambda/3$ for the basic representation shown in Figure 6.36(a). Given an animation frame rate of 60 frames per second, this establishes an upper bound of 20 messages per second that can be represented.

There are many ways in which the correspondence limitation can be overcome by giving the graphical elements a different shape, orientation, or color. Two possibilities are illustrated in Figure 6.36(b) and (c). In one, the gray values of the elements are varied from message to message; in the other, the shapes of the elements are varied. Research with element shapes suggests that correspondence of shape is more important than correspondence of color in determining perceived motion (Caelli et al., 1993). In a series of experiments that examined a variety of enhanced representations like those illustrated in Figure 6.36(b) and (c), Fleet (1998) found that the average phase shift per animation frame could be increased to 3λ before correspondence was lost. Given an animation frame rate of 60 frames per second, this translates to an upper bound of 180 messages per second that can be represented using animation.

Of course, when the goal is to visualize high traffic rates, there is no point in representing individual messages in detail. Most digital communications systems transfer millions of data packets per second. What is important at high data rates is an impression of data volumes, the direction of traffic flow, and large-scale patterns of activity.

Form and Contour in Motion

A number of studies have shown that people can see relative motion with great sensitivity. For example, contours and region boundaries can be perceived with precision in fields of random dots if defined by differential motion alone (Regan, 1989; Regan and Hamstra, 1991). Human sensitivity to such motion patterns rivals our sensitivity to static patterns; this suggests that motion is an underutilized method for displaying patterns in data.

For purposes of data display, we can treat motion as an attribute of a visual object, much as we consider size, color, and position to be object attributes. We evaluated the use of simple sinusoidal motion in enabling people to perceive correlations between variables (Limoges et al., 1989). We enhanced a conventional scatter plot representation by allowing the points to oscillate sinusoidally, either horizontally or vertically (or both) about a center point. An experiment was conducted to discover whether the frequency, phase, or amplitude of point motion was the most easily "read." The task was to distinguish a high correlation between variables from a low one. A comparison was made with more conventional graphical techniques, including using point size, gray value, and x,y position in a conventional scatter plot. The results showed that data mapped to phase was perceived best; in fact, it was as effective as most of the more conventional techniques, such as the use of point size or gray value. In informal studies, we also showed that motion appears to be effective in revealing clusters of distinct data points in a multidimensional data space (see Figure 6.37). Related data shows up as clouds of points moving together in elliptical paths, and these can be easily differentiated from other clouds of points.

Moving Frames

Perceived motion is highly dependent on its context. Johansson (1975) has demonstrated a number of grouping phenomena that show that the brain has a strong tendency to group moving objects in a hierarchical fashion. One of the effects he investigated is illustrated in Figure 6.38. In this example, three dots are set in motion. The two outer dots move in synchrony in a horizontal direction. The third dot, located between the other two, also moves in synchrony but in an oblique direction. However, the central dot is not perceived as moving along an oblique path. Instead, what is perceived is illustrated in 6.38(b). An overall horizontal motion of the entire group of dots is seen; within this group, the central dot also appears to move vertically.

A rectangular frame provides a very strong contextual cue for motion perception. It is so strong that if a bright frame is made to move around a bright static dot in an otherwise

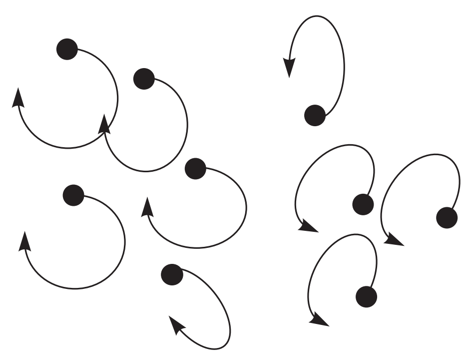

Figure 6.37 An illustration of the elliptical motion paths that result when variables are mapped to the relative phase angles of oscillating dots. The result is similar elliptical motion paths for points that are similar. In this example, two distinct groups of oscillating dots are clearly perceived.

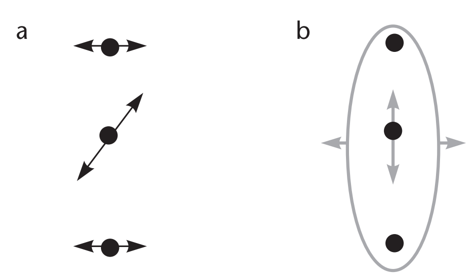

Figure 6.38 When dots are set in synchronized motion, as shown in (a), what is actually perceived is shown in (b). The entire group of dots is seen to move horizontally, and the central dot moves vertically within the group.

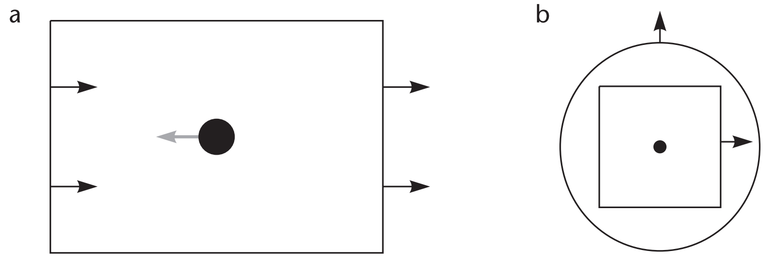

Figure 6.39 (a) When a stationary dot is placed within a moving frame in a dark room, it is the dot that is perceived to move in the absence of other cues. (b) The effect is hierarchical.

completely dark environment, it is often the static dot that appears to move (Wallach, 1959). Wallach also showed that the effect works in a hierarchical fashion. Thus, the perceived motion of the static dot in Figure 6.39(b) is strongly influenced by the motion of a surrounding square frame, but it is much less influenced by the motion of the circle outside the square.

Computer animation is often used in a straightforward way to display dynamic phenomena, such as a particle flow through a vector field. In these applications, the main goal from a perceptual point of view is to bring the motion into the range of human sensitivities. The issue is the same for viewing high-speed or single-frame movie photography. The motions of flowers blooming or bullets passing through objects are speeded up and slowed down, respectively, so that we can perceive the dynamics of the phenomena. Humans are reasonably sensitive to motion ranging from a few millimeters per second to a few hundred millimeters per second for objects viewed at normal screen distances. Generally, the data animator should aim for motion in the midrange of a few centimeters per second. (See Chapter 2 for some of the basic issues related to motion sensitivity.)

The use of motion to help us distinguish patterns in abstract data is at present only a research topic, albeit a very promising one. One application of the research results is the use of frames to examine dynamic flow field animations. Frames can be used as an effective device for highlighting local relative motion. If we wish to highlight the local relative motion of a group of particles moving through a fluid, a rectangular frame that moves along with the group will create a reference area within which local motion patterns can emerge.

Another way in which motion patterns are important is in helping us to perceive visual space and rigid 3D shapes. This topic is covered in Chapter 8 in the context of the other mechanisms of space perception.

Expressive Motion

Using moving patterns to represent motion on communication channels, or in vector fields, is a rather obvious use of motion for information display, but there are other, more subtle uses. There appears to be a vocabulary of expressive motion comparable in richness and variety to the vocabulary of static patterns explored by the Gestalt psychologists. In the following sections, some of the more provocative results are discussed, together with their implications for data visualization.

Perception of Causality

When we see a billiard ball strike another and set the second ball in motion, we perceive that the motion of the first ball *causes* the motion of the second, according to the work of Michotte (translated 1963). Michotte's book *The Perception of Causality* is a compendium of dozens of experiments, each showing how variations in the basic parameters of velocity and event timing can radically alter what is perceived. He conducted detailed studies of the perception of interactions between two patches of light and came to the conclusion that the perception of causality can be as direct and immediate as the perception of simple form. In a typical experiment, illustrated in Figure 6.40, one rectangular patch of light moved from left to right until it just touched a second patch of light, then stopped. At this point, the second patch of light would start to move. This was before the advent of computer graphics, and Michotte conducted his experiments with an apparatus that used little mirrors and beams of light. Depending on the temporal relationships between the moving-light events and their relative velocities, observers reported different kinds of causal relationships, variously described as "launching," "entraining," or "triggering."

Precise timing is required to achieve perceived causality. For example, Michotte found that for the effect he called *launching* to be perceived, the second object had to move within 70 milliseconds of contact; after this interval, subjects still perceived the first object as setting the second object in motion, but the phenomenon was qualitatively different. He called it *delayed launching*. Beyond about 160 milliseconds, there was no longer an impression that one event caused the other; instead, unconnected movements of the two objects were perceived. Figure 6.41 provides a reproduction of some of his results. For causality to be perceived, visual events must be synchronized within at least one-sixth of a second. Given that virtual-reality animation often occurs at only about 10 frames per second, events should be frame-accurate for clear causality to be perceived.

If an object makes contact with another and the second object moves off at a much greater velocity, a phenomenon that Michotte called *triggering* is perceived. The first object does not seem to cause the second object to move by imparting its own energy; rather, it appears that contact triggers propelled motion in the second object.

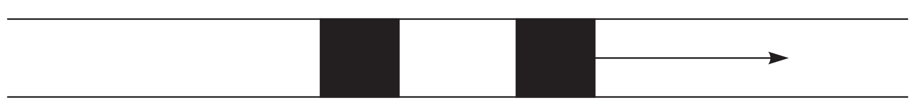

Figure 6.40 Michotte (1963) studied the perception of causal relationships between two patches of light that always moved along the same line but with a variety of velocity patterns.

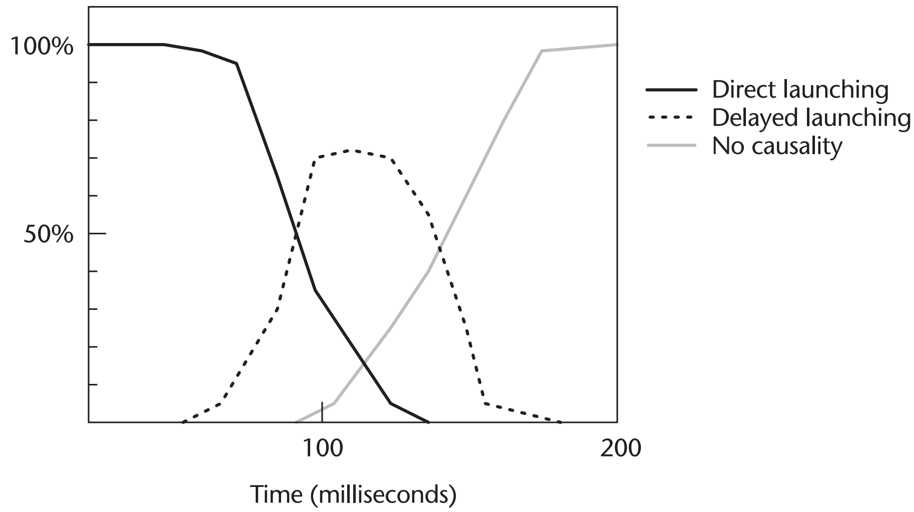

Figure 6.41 From Michotte (1963). When one object comes into contact with another and the second moves off, the first motion may be seen to cause the second if the right temporal relationships exist. The graph shows how different kinds of phenomena are perceived, depending on the delay between the arrival of one object and the departure of the other.

More recent developmental work by Leslie and Keeble (1987) has shown that infants at only 27 weeks of age can perceive causal relations such as launching. This would appear to support the contention that such percepts are in some sense basic to perception.

The significance of Michotte's work for data visualization is that it provides a way to increase the expressive range beyond what is possible with static diagrams. In a static visualization, the visual vocabulary for representing relationships is quite limited. To show that one visual object is related to another, we can draw lines between them, we can color or texture groups of objects, or we can use some kind of simple shape coding. The only way to show a causal link between two objects is by using some kind of conventional code, such as a labeled arrow. However, such codes owe their meaning more to our ability to understand conventional coded language symbols than to anything essentially perceptual. This point about the differences between language-based and perceptual codes is elaborated in Chapter 9. What Michotte's work gives us is the ability to significantly enrich the vocabulary of things that can be immediately and directly represented in a diagram.

Perception of Animate Motion

In addition to the fact that we can perceive causality using simple animation, there is evidence that we are highly sensitive to motion that has a biological origin. In a series of now-classic studies, Gunnar Johansson attached lights to the limb joints of actors (Johansson, 1973). He then produced moving pictures of the actors carrying out certain activities, such as walking and

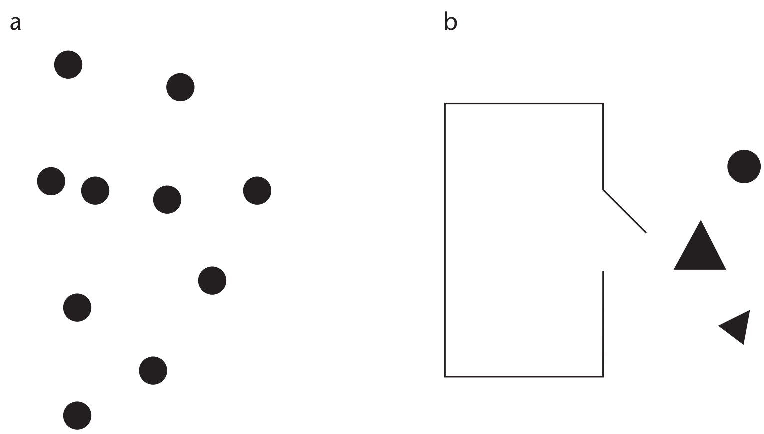

Figure 6.42 (a) In Johansson's (1973) experiments, a pattern of moving dots was produced by making a movie of actors with lights attached to parts of their bodies. (b) Heider and Semmel (1944) made a movie of simple geometric shapes moving through complex paths. Viewers of both kinds of displays attribute anthropomorphic characteristics to what they see.

dancing. These pictures were made so that only the points of light were visible, and, in any given still frame, all that was perceived was a rather random-looking collection of dots, as shown in Figure 6.42(a). A remarkable result from Johansson's studies was that viewers of the animated movies were immediately conscious of the fact that they were watching human motion. In addition, they could identify the genders of the actors and the tasks they were performing. Some of these identifications could be made after exposures lasting only a small fraction of a second.

Another experiment pointing to our ability to recognize form from motion was a study by Heider and Semmel (1944). In this study, an animated movie was produced incorporating the motion of two triangles and a circle, as shown in Figure 6.42(b). People viewing this movie readily attributed human characteristics to the shapes; they would say, for example, that a particular shape was angry, or that the shapes were chasing one another. Moreover, these interpretations were consistent across observers. Because the figures were simple shapes, the implication is that patterns of motion were conveying the meaning. Other studies support this interpretation. Rimé et al. (1985) did a cross-cultural evaluation of simple animations using European, American, and African subjects, and found that motion could express such concepts as kindness, fear, or aggression, and there was considerable similarity in these interpretations across cultures, suggesting some measure of universality.

Enriching Diagrams with Simple Animation

The research findings of Michotte, Johansson, Rimé, and others suggest that the use of simple motion can powerfully express certain kinds of relationships in data. Animation of abstract shapes can significantly extend the vocabulary of things that can be conveyed naturally beyond what is possible with a static diagram. The key result, that motion does not require the support of complex depictive representations (of animals or people) to be perceived as animate, means that simplified motion techniques may be useful in multimedia presentations. The kinds of animated critters that are starting to crawl and hop over Web pages are often unnecessary and distracting. Just as elegance is a virtue in static diagrams, so is it a virtue in diagrams that use animation. A vocabulary of simple expressive animation requires development, but research results strongly suggest that this will be a productive and worthwhile endeavor. The issue is pressing, because animation tools are becoming more widely available for information display systems. More design work and more research are needed.

Conclusion

The brain is a powerful pattern-finding engine; indeed, this is the fundamental reason why visualization techniques are becoming important. There is no other way of presenting information so that structures, groups, and trends can be discovered among hundreds of data values. If we can transform data into the appropriate visual representation, its structure may be revealed. However, not all patterns are equally easy to perceive. The brain appears to be especially good at discovering linear features and distinct objects, so much so that the discovery of spurious patterns should always be a concern. Because the brain is a pattern-finding engine, patterns may be perceived even where there is only visual noise.

Much of the material presented in this chapter, especially the Gestalt laws of pattern perception, leads to rules that seem obvious to any visual designer. Nevertheless, it is surprising how often these design rules are violated. A common mistake is that related data glyphs are placed far apart in displays. Another is that closed contours are used in ways that visually segment a display into regions that make it difficult, rather than easy, to comprehend related information. The use of windows is often to blame, because they result in strong framing effects, which can cause confusion if used inconsistently.

For information to be clearly related, the visual structure should reflect relationships between data entities. Placing data glyphs in spatial proximity, linking them with lines, or enclosing them within a contour will provide the necessary visual structure to make them seem related. In terms of seeing patterns in rather abstract data displays, perception of contours is likely to be especially important. The visual system contains a number of mechanisms for finding contours. These contours can be simple lines, dots, or other features in a linear pattern; boundaries between regions of different textures, different colors, different motion; or even illusory contours.

For the researcher and for those interested in finding novel display techniques, the effective use of motion is suggested as a fertile area for investigation. Patterns in moving data points can be perceived easily and rapidly. Given the computing power of modern personal computers, the opportunity exists to make far greater use of animation in visualizing information.