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When What Meets Where

Maggie Shiffrar

How does the visual system determine in which direction an object moves? This question has fascinated generations of researchers because it encompasses so many of the fundamental issues in psychology. One of these concerns how the human perceptual system uniquely solves patterns of stimulation having an infinite number of possible interpretations. For example, in the case of vision, a single two-dimensional projected image is often consistent with an infinite number of different three-dimensional physical objects. Nonetheless, human observers are able to uniquely interpret such underdetermined images. What enables observers to systematically in-

terpret inherently ambiguous visual images?

Many researchers have argued that the visual system uses constraints to limit the number of possible interpretations of a projected image.^{1,2} A constraint can be defined as an assumption or prior knowledge about the nature of the physical world. A visual system reduces the number of possible image interpretations by rejecting any interpretation inconsistent with the system's previously defined constraints. Most current models of the visual system describe it as a multilayered, richly interconnected hierarchical structure.³ Because so much information is lost in the imaging process, constraints are required at many different levels within the visual system. Some constraints are needed during the earliest stages to interpret small, local regions of an image. These low-level constraints play a role in the analysis of relatively small object segments or features. An edge detector that analyzes small parts of an image is one example of a low-level visual constraint. Later stages in the visual system must combine the out-

puts of the earlier, spatially restricted analyses. Object-based constraints may be applied during some of these later stages so that information regarding entire objects can be recovered uniquely. Object permanence (i.e., the tendency to assume the continued existence of an object even when it disappears momentarily) is an example of a higher level, object-based constraint that the visual system appears to use in the interpretation of motion.¹

The proposal that the visual system uses a hierarchy of various constraints leads to numerous questions. How do constraints interact within and across levels of analysis? Are some constraints applied to all images and others reserved for particular classes of images? To address these questions, my colleagues and I have constructed dynamic stimuli that place different constraints in conflict with one another. By examining how people interpret these images, we can ascertain how visual constraints are organized, invoked, and applied. The purpose of this article is to examine when object-based constraints control the interpretation of moving images. I begin with a discussion of how low-level, feature-based motion constraints compete with higher level, object-based motion constraints. I then examine the conditions under which

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an object's identity influences interpretations of its movement—that is, when what we see determines where we see it.

GENERALIZED OBJECT CONSTRAINTS

Current models of visual motion processing are based on the assumption that units in the lower levels of the visual system process local information through relatively small receptive fields. The measurement of visual motion through such spatially limited receptive fields is fundamentally problematic. For example, the motion of a translating homogeneous edge measured through a

small window or receptive field is ambiguous because the component of motion parallel to the edge cannot be measured. As a result, all moving edges with the same perpendicular component of motion but differing parallel components of motion will appear to move identically, as shown in Figure 1. This local ambiguity, known as the aperture problem, has received extensive study because both biological and computational visual systems have receptive fields limited in size. Human observers appear to overcome the aperture problem with a local rigidity constraint.^{4,5} This constraint is based on the assumption that neighboring points belonging to the same contour will most likely move with identical velocities. As a result, this constraint selects for local motion

interpretations that minimize velocity differences between points composing the same continuous contour.

Once the motion of a visual image has been measured through spatially limited receptive fields, the visual system must then combine these local motion signals across different regions of the image. Again, the visual system is confronted with an ambiguous situation, as these local signals can be combined in an infinite number of different patterns. The combination of local motion signals into a global interpretation of object motion is a critical step in all models of motion perception. Many models have proposed that the visual system solves this problem with an object rigidity constraint.⁶ This constraint selects for those image interpretations that are consistent with rigid objects.

When an object rigidity constraint and a local rigidity constraint lead to different interpretations of an image, which constraint does the visual system rely on to uniquely solve that image? To what extent does the visual system use global constraints that incorporate characteristics of entire objects to direct the combination of motion signals across an image? Misha Pavel, from New York University; Jean Lorenceau, from Université de Paris V; and I have attempted to answer this question by studying the situation represented in Figure 2. Imagine a polygon figure (in this case, a square) translating across the image plane. The movement of the polygon is measured by four hypothetical receptors that are represented in the figure as circles. As a result of the aperture problem, the motion measured within each receptor is inherently ambiguous. This stimulus is of interest because it is interpreted differently depending on whether a local rigidity constraint or an object rigidity constraint dominates the interpretation process (see Fig. 2b). Which kind of constraint do human observers use? For example,

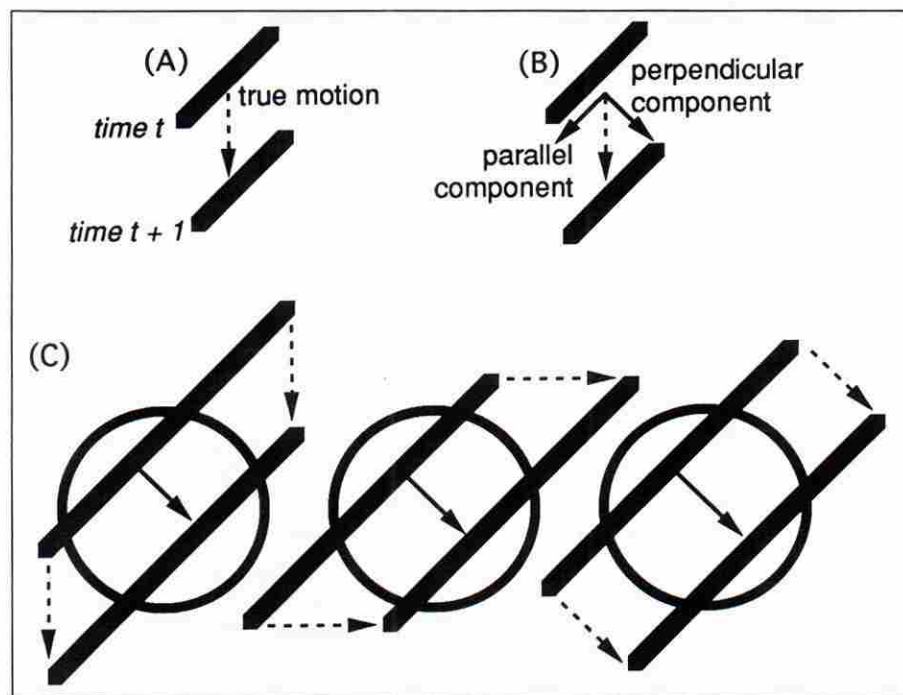


Fig. 1. The aperture problem. (a) The true downward translation (represented by the dashed arrow) of a vertically translating line segment can be decomposed into one component that is perpendicular to the line and a second component that is parallel to the line, as represented in (b) by the solid arrows. Whenever a moving line is viewed through a relatively small aperture, represented in (c) by circles, the parallel component of motion cannot be measured because displacements parallel to a homogeneous line produce no visible change within the aperture. Only the perpendicular component of motion causes a visible change within the aperture. Thus, an infinitely large family of different motions (having the same perpendicular but differing parallel components of motion) all appear to be identical. Three examples are illustrated in (c): These translations (one vertical, one horizontal, and one oblique) all produce exactly the same motion within the aperture.

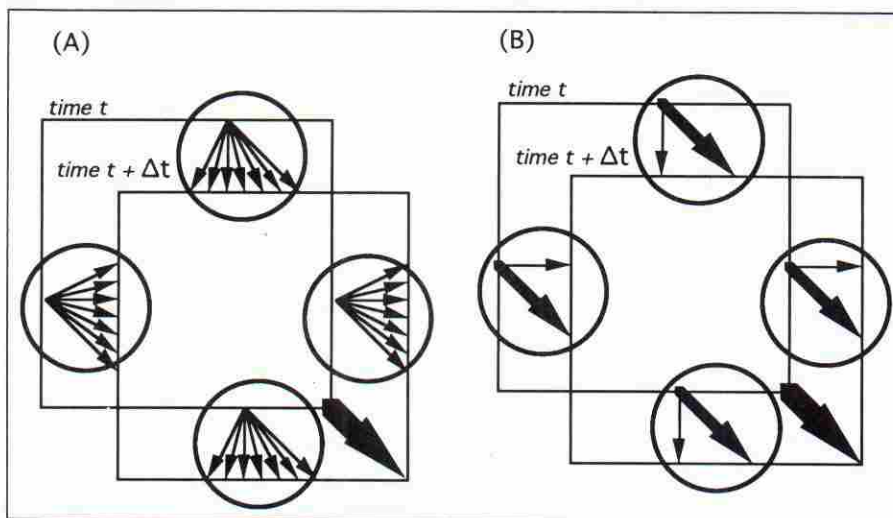


Fig. 2. A square translating downward and to the right seen at two different times. The motion of the square is measured by four receptors that are represented here as circles. (a) As a result of the aperture problem, the motion measured within each receptive field is inherently ambiguous. How does the visual system determine the movement of the translating square from these four ambiguous measurements? (b) If a local rigidity constraint is applied to the output of each receptor, the interpreted direction of translation will be perpendicular to each contour, as represented by the thin arrows. In contrast, an object rigidity constraint will select the interpretation of motion represented here by the thick arrows. Which constraint is more powerful?

in the present case, if an observer knows that the edges visible through the four apertures belong to the same translating, rigid square figure, will that observer rely on a local rigidity constraint (and interpret each edge independently of the other edges) or an object rigidity constraint (and interpret all the edges so they are consistent with a rigidly translating square)?

Our behavioral studies suggest that prior knowledge of object rigidity is not used to disambiguate motion information during the integration of local motion signals. When the object rigidity constraint and the local rigidity constraint lead to different interpretations of the same image, the visual system defaults to the low-level, locally rigid solution. That is, observers have great difficulty combining individually ambiguous motion signals across different regions of an image, even when they know the exact shape of the underlying object. For example, if the outlined square figure shown in Figure 2 translates back and forth and is visible only through the four stationary

apertures, observers do not perceive a rigidly translating square. Instead, observers consistently perceive the four visible contours moving independently of one another, each translating in the direction perpendicular to its orientation. This powerful effect is not altered by the observer's prior knowledge of object shape, object rigidity, or object movement.

This demonstration is particularly surprising because numerous researchers have proposed that observers of moving objects rely heavily on an object rigidity constraint and therefore are biased toward selecting interpretations that are consistent with rigid objects. It may be that the visual system invokes an object rigidity constraint only when that constraint leads to an image interpretation that is not inconsistent with any of the locally unambiguous motion signals that may be present in an image. Such unambiguous signals can be obtained from certain image features, such as contour discontinuities (e.g., corners), that provide both parallel and perpendicular components of motion.

Thus, although many current theories propose that the visual system overcomes the ambiguity of individual motion measurements by combining motion signals across differently oriented contours, under various experimental conditions, human observers cannot perform this task: Observers are unable to accurately combine rotation signals across disconnected contours arising from a single rotating polygon⁵ and perform poorly on tasks requiring the combination of translation signals across disparate polygon contours.⁷ Under numerous conditions, high-level, object-based information does not appear to influence the interpretation of visual motion. Instead, it seems that object motion may be determined independently of various aspects of object identity.

OBJECT-SPECIFIC CONSTRAINTS

However, intriguing recent research on the visual perception of biological motion indicates that, under a strictly limited set of conditions, the identity of an object may strongly influence the interpretation of its motion. Neurophysiologist David Perrett and his colleagues at the University of St. Andrews have examined the responsiveness of individual cells in the anterior region of the superior temporal sulcus (STS, an area involved in later stages of visual analysis) to a wide variety of visual images. Their findings demonstrate clearly that cells in this area are selectively responsive to precise combinations of biological forms and movements. Through a series of single-cell recordings in the macaque STS, Perrett has identified numerous cells that respond selectively to moving human and primate bodies and yet remain unresponsive to moving inanimate control objects.⁸ These findings are particularly interesting in light of proposals

that motion information is processed separately from object identification—in the dorsal (or “where”) and ventral (or “what”) visual pathways, respectively.⁹ More recent research suggests that these two pathways do converge in the STS.¹⁰ Thus, Perrett’s findings suggest that although object identification and motion analyses generally proceed separately, these processes may interact in the analysis of certain types of biological motion.

Jennifer Freyd, from the University of Oregon, and I set out to determine if motion perception by human observers might be influenced by object identity when stimuli are biologically based. Apparent motion of the human body was the situation of interest because apparent motion, like the aperture problem, illustrates an inherent ambiguity in the interpretation of visual images. In classic demonstrations of apparent motion, two stationary dots are presented sequentially under appropriate spatiotemporal conditions such that the two dots appear as a single dot moving back and forth. This situation is ambiguous because there is an infinite number of possible paths of motion connecting any two points. How does the visual system

uniquely interpret a single path of apparent motion? Traditionally, researchers have argued that the visual system solves this problem with a shortest path constraint, which selects the interpretation that requires the shortest path of motion. Evidence supporting the use of this constraint comes from a series of classic apparent motion studies that relied on reduced stimuli such as dots and lines. Under these conditions, human observers are strongly biased toward perceiving the shortest path of apparent motion. Such research has been used to support the proposal that an object’s identity does not influence the interpretation of its motion.

Biological motion, although of considerable importance to human observers, often violates this shortest path constraint. Are observers of human movements more likely to perceive apparent motion paths that are consistent with the movement limitations of the human body or paths that traverse the shortest possible distance? To answer this question, Freyd and I created stimuli consisting of photographs of a human model in different positions so that biomechanically possible paths of motion conflicted with the shortest

possible paths, as illustrated in Figure 3.

When subjects viewed these stimuli in a tachistoscope, the perceived paths of motion changed with the temporal separation between the onsets of the stimuli (i.e., stimulus onset asynchrony, or SOA). At short SOAs, subjects tended to see the shortest, physically impossible motion path. However, with longer SOAs, observers were increasingly likely to see longer apparent motion paths.¹¹ These relatively long paths of apparent motion were of a very specific type; that is, they were those paths consistent with normal movements of the human body. In contrast, when viewing photographs of inanimate control objects, subjects in subsequent control experiments consistently perceived the shortest possible path of apparent motion at all temporal separations. Moreover, when viewing photographs of a human model positioned so that the shortest movement path was the physically correct path, observers reported seeing this shortest path at all temporal separations.¹²

There are conditions under which relatively long paths of apparent motion can be seen with nonbiological stimuli. For example, Foster has shown that orientation can influence the perceived apparent motion path of an outlined rectangle.¹³ However, the identity of such an inanimate stimulus, whether a brick or an eraser, does not appear to constrain path choice. This combination of results supports the hypothesis that, when given enough time, the visual system constructs paths of apparent motion that are consistent with the biomechanical limitations of the human body. This behavioral finding is compatible with the neurophysiological research described at the beginning of this section because both suggest that object identity and motion signals may be integrated during the analysis of certain types of biological motion.

It is interesting that such object-

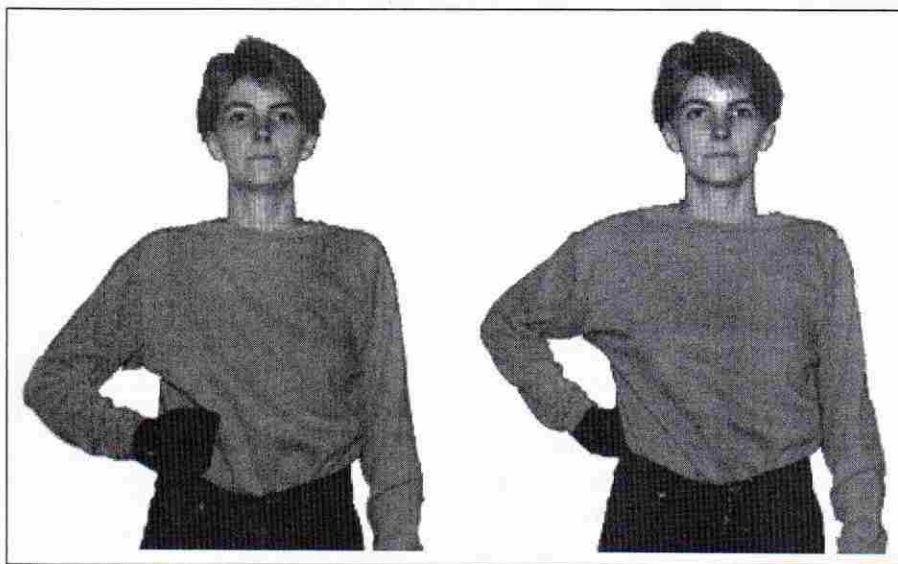


Fig. 3. A black-and-white rendition of a stimulus pair used in the apparent motion studies of Shiffrar and Freyd.¹¹ Notice that the shortest possible path of motion is physically impossible.

specific information appears to constrain percepts of apparent motion only when sufficient processing time is available (generally speaking, when the SOA is greater than approximately 200 ms). This requirement for sufficient processing time is consistent with other visual motion studies involving biological movement. Consider, for example, Gunnar Johansson's classic studies of the perception of human locomotion. When viewing a group of moving dots that correspond to light sources attached to the main joints of a human walker, observers perceive a compelling impression of a walking person, but only if the stimulus is displayed for at least approximately 200 ms.¹⁴ Similarly, Perrett and his colleagues found that those STS cells conjointly sensitive to biological movements and forms have relatively long mean response latencies of approximately 150 ms (i.e., take an average of about 150 ms to respond after being stimulated with light). It would be particularly interesting to examine the possible relationship between the long processing time for accurate perception of biological motion and the relatively long response latencies of cells in the STS.

Taken together, these findings suggest that interpretation of visual apparent motion with biological stimuli is significantly constrained by the movement limitations of biological forms. Intriguing recent research on the visual perception of biological motion by cats suggests that this sensitivity to biological motion may be a fundamental specialization common to many different mammalian visual systems.¹⁵ It will be important for future studies to investigate what categories and representations of biological stimuli facilitate analysis by specialized systems that integrate object identity and movement signals.

CONCLUSIONS

Because the interpretation of visual images is inherently ambiguous, constraints can be used to limit the number of possible solutions to any image. Whether high-level, object-based constraints are used to direct the interpretation of an object's movement may depend on the type of object under consideration. As a rule, identification of objects and analysis of spatial relationships are thought to proceed independently within the visual system. For example, when the visual system combines motion signals across different image regions in order to interpret an object's direction of movement, little weight is given to global, object information. That is, moving contours appear to be interpreted in the same manner irrespective of whether the contours belong to the same rigid object or different objects. This segregation of object identification and motion processing does not appear to be maintained throughout the entire visual system, however. Evidence from numerous researchers suggests that spatial perception and object identification may be brought together in the analysis of biological motion. Although future research in this area will certainly clarify understanding of higher level visual processing, for the moment, it appears that the analysis of some types of biological motion may hold a special status within the visual system, benefiting from a convergence of object and movement information.

In conclusion, although simple stimuli such as dots and lines may suffice for studying low-level visual analyses, more complex and meaningful stimuli may be required for studying later stages of visual analysis, which receive more highly processed information. Differences in

visual motion perception before and after "what" converges with "where" provide a particularly interesting illustration of this principle.

Acknowledgments—Preparation of this review was supported by Grant EY09931 from the National Institutes of Health and Grant INT16895 from the National Science Foundation. I wish to thank Tom Albright, Ian Gold, Nancy Kanwisher, and Romy Spitz for numerous insightful comments on an earlier version of the manuscript.

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