

## PHENOMENAL REPORT

## Perpetual rotation of real and illusory shapes

Yuki Kobayashi<sup>1,2\*</sup> and Arthur G. Shapiro<sup>1,3</sup>

<sup>1</sup>Department of Computer Science, American University, Washington DC, USA; <sup>2</sup>Research Organization of Open Innovation and Collaboration, Ritsumeikan University, Ibaraki, Osaka, Japan; <sup>3</sup>Department of Psychology, American University, Washington DC, USA

**Abstract**

The field of perceptual psychology has long been interested in determining how the perception of global shape arises from the interplay between local elements. We investigate this issue by combining the Kanizsa square illusion (an illusory square that emerges from the placement of four Pacman-like shapes) with edge motion illusions (the illusory continuous motion perceived when the luminance of a stationary edge and neighboring fields is modulated in time). Our basic demonstration builds on cascading levels of motion signals: illusory motion at a point is known to be ambiguous as to direction (the aperture problem); illusory motion of edges in isolation (here, the local elements) is perceived as either vertical or horizontal; illusory motion of edges when combined at right angles is perceived as diagonal; and illusory motion of the Kanizsa square (the global percept) is perceived as rotational. The perception of a rotating square suggests that the interpretation of the local motion signals depends on the global context and is, perhaps, informed by a tendency to perceive shapes as rigid. We created variants of the original figure to identify and assess critical factors of this phenomenon, including changes in temporal phase and amodal completion of motion. Our investigations with the basic figure and variants – examples of multistable motion illusions – demonstrate that observers can easily switch their attention between perceptual modes constructed separately from the local and global motion information.

**Keywords:** *illusory contours; motion illusion; Gestalt perception; bistable perception; rotation; tilt*

To access the movies for this article, please visit the article landing page or read the HTML version if the paper where all moves are embedded

**Edited by:**

Stuart Anstis, University of California, USA

**Reviewed by:**

Priscilla Heard, University of the West of England, UK

Walter Gerbino, University of Trieste, Italy

Received: 15 April 2024; Revised: 17 December 2024; Accepted: 10 January 2025; Published: 27 March 2025

Typical demonstrations of Gestalt grouping show images that contain qualities that would not be expected if one were to examine the image's local elements separately, and thus, they illustrate the accurate but slightly clichéd statement, 'The whole is more than the sum of its parts'. Classic examples are beta movement (Wertheimer, 1912/2012; see Steinman et al., 2000) and the Kanizsa square (Kanizsa, 1976). In the beta movement, two lights blink on and off, but when lights are modulated in antiphase, the perception switches to a single light that moves back and forth. In the Kanizsa square, the elements are four disks, each with a missing pizza slice (a shape referred to as a Pacman in reference to the 1980s video game); when the four Pacmen are appropriately aligned, an illusory square surface appears to be sitting on top of four

circles. In both examples, the global percept (i.e. the whole, or the back-and-forth motion, or the illusory square) contains a quality not found in the isolated figural elements (i.e. the parts, or the blinking lights, or the Pacmen).

The question of how the global percept arises from the interplay between local elements has been of longstanding interest to perceptual psychology. Historically, Gestalt psychology framed the problem in terms of generalizable rules that take precedence over local sources of information, whereas structuralist frameworks attended to the effects of the individual elements and their interaction (a molar approach vs. a molecular approach, as Boring [1936] phrased in his review of Koffka's classic book [1935]). A more contemporary framework is that perceptual organization arises from a Bayesian synthesis of mid-level

\*Correspondence: Yuki Kobayashi. Email: [lpstb50@gmail.com](mailto:lpstb50@gmail.com)

encodings of spatial and temporal information (e.g. Anderson, 2020; Feldman, 2015). Bayesian approaches allow for structure to be inferred from local elements based on the situational context, the viewer’s perceptual history, and assumptions that the viewer makes about the nature of light and the actions of objects. Such approaches have been very successful at producing models that can account for a range of different perceptual phenomena (see, for instance, Froyen et al., 2015; Geisler & Kersten, 2002).

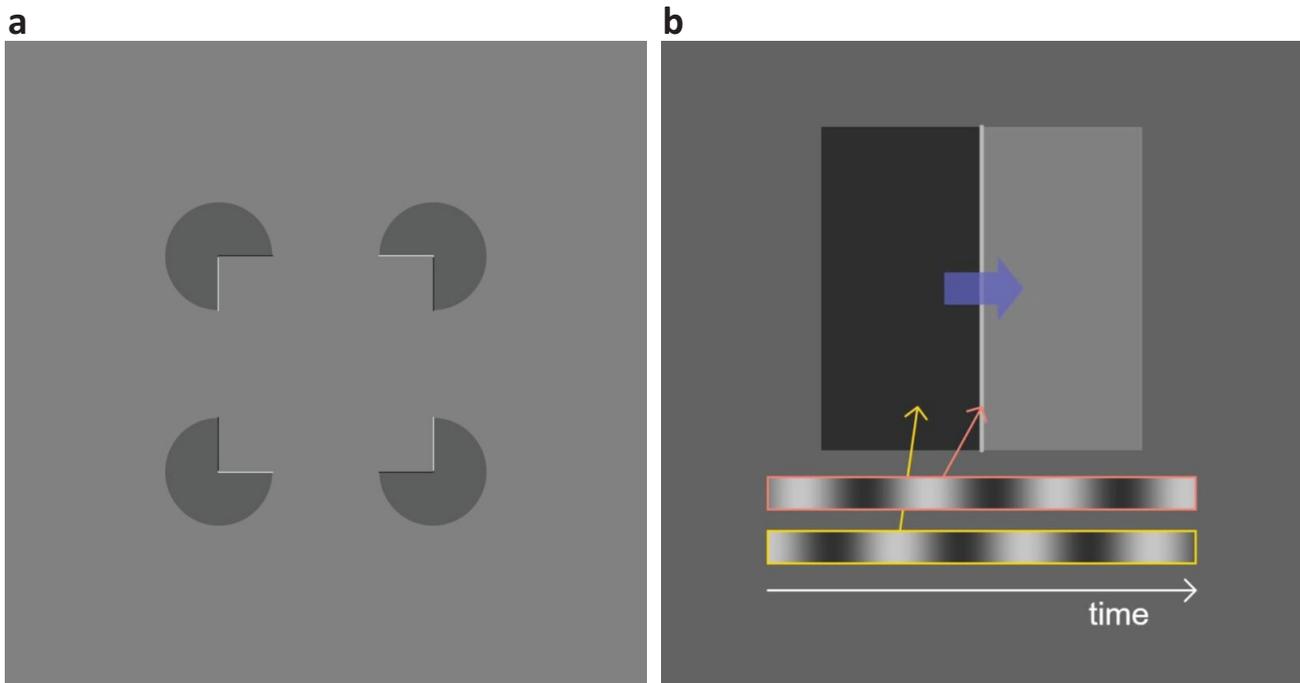
Implicit in all these approaches is that while a single description of a stimulus is often convenient to make measurements in an experiment, most shapes allow for multiple interpretations depending on the scale of attention. Indeed, while the literature on Bayesian approaches to understanding global form is large and growing and has proved very useful for machine learning and categorization, it does seem that in order to make measurements of perception, one is forced to categorize the object of a perceptual response, such as asking the observer, ‘Do you see X, or do you see Y?’ Such forced categorization can lead to an underappreciation of the complexity of the perceptual interpretation, a fact that was often stressed in the older literature. For instance, Koffka (1935) and others pointed out that figure and ground form a ‘duo-organization’, where one is ‘thing’ and the other is framework (Boring, 1936), and Katz (1935) highlighted ‘modes of appearance’. See also Stiny

(2006), who emphasized that the shapes can be built through a type of grammar that can lead to multiple interpretations.

Most of the demonstrations in this paper consist of shapes constructed by combining simple isolated motion edges. The demonstrations are built on a construction presented by Flynn and Shapiro (2018); artwork expanding on this idea has also been presented on a social network (Jagarikin, 2023). Here, we show that the emergent percept of the global motion – whether it arises in an illusory or real shape – cannot be predicted by the motion of the local elements. Observers can perceive either the global emergent motion or local motion by switching their attention: We show that (1) globally integrated motion can create a tilting appearance of vertical or horizontal edge orientation even though the tilt is not present in the isolated elements, and (2) the integration of local motion into a global figure that moves can be achieved even with illusory shapes due to processes that allow for object construction. The perceptions that arise from the integration of local motion strips, therefore, create a conflict between two appearances, which creates a form of motion bistability that adds to the complexity of the phenomenon and may be useful in understanding perceptual organization.

**The basic demonstration**

The basic demonstrations consist of four Kanizsa elements (Pacmen) configured to make an illusory square;



**Movie 1.** (a) The basic demonstration of the rotating Kanizsa square. The illusory square appears to perpetually rotate counterclockwise and tilt toward the left. (b) An explanation of how luminance modulation signals motion (Flynn & Shapiro, 2018). In this display, a modulating strip bordering a gray area (right half), and another modulating area (left half) appears to move rightward (the bluish arrow indicates apparent motion). The luminance levels in the strip and the left area modulate sinusoidally, and they have a slight phase difference (the two horizontal gratings below the square indicate the luminance modulation over time). As can be seen in the x,t plot, the difference in the luminance levels creates a slope direction that is consistent with perceived motion.

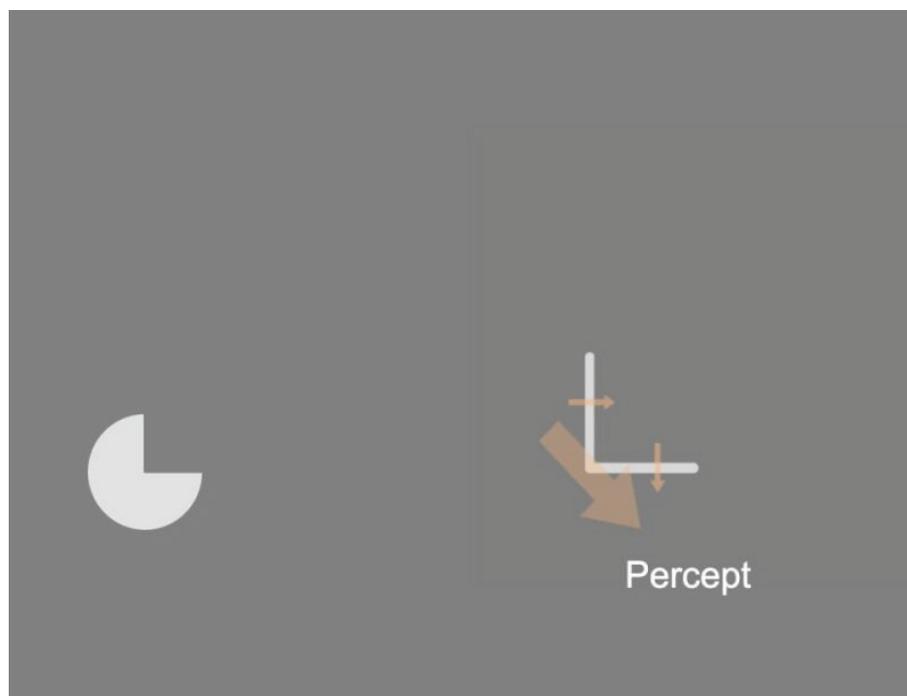
each Pacman has a thin vertical strip and a thin horizontal strip defining their mouth. In Movie 1a, the luminance levels of the Pacmen and the strips modulate in time at approximately 2 Hz. Even though the strips are stationary, the modulation makes them appear to move (Flynn & Shapiro, 2018). The motion of the central square is similar to that of the central diamond in Flynn and Shapiro's demonstration (i.e. the object is gray, and the background luminance is modulating in the present demonstration).

Movie 1b shows the edge strip enlarged and in isolation. The direction of the motion of the central square is determined by the phase of the strip modulation relative to the modulation adjoining the Pacmen (Flynn & Shapiro, 2018). For Movie 1a, the motion of the central square is created by appropriately adjusting the luminance phases of the Pacmen's strips. This method for creating motion is the same as reverse phi and has the same underlying principle as several other methods to produce apparent motion in static objects (Anstis & Rogers, 1975; Gregory & Heard, 1983; Kitaoka, 2006; Mather & Murdoch, 1999; Shapiro, 2021).

There are two types of apparent motion: the local motion of the strips and the global motion of the square. As has been shown elsewhere (the aperture problem; e.g. Murakami, 2004), the direction of local motion cues can be ambiguous and is determined by contextual information. However, for edges in isolation (Movie 1b), the motion appears orthogonal to the line presumably due to a principle of energy minimization or summation of all symmetric possible directions

(Stumpf, 1911, translated and commented on by Todorović, 1996; Wallach, 1935, translated and commented on by Wuerger et al., 1996). So, while the direction of motion at each point is, in principle, indeterminate, extended edges in isolation appear to move up or down if they are horizontal and appear to move left or right if they are vertical. The direction (up or down; left or right) depends on the modulation phase of the strip compared to the modulation phase of the adjoining Pacman. In the current configuration, a  $90^\circ$  modulation compared to the modulation of the Pacman makes the strips move inward, and a  $-90^\circ$  modulation compared to the Pacman makes the strip move outward.

The integration of the motion produces a paradox, or 'conflict', between the global and local contextual information. The global motion of the square depends on the motion of all the edges in comparison to one another. That is, in Movie 1a, the central square appears to be rotating counterclockwise, but the motion of each strip, when observed in isolation, is perceived as perpendicular to the motion of the other strip in the same Pacman (in the upper right Pacman, the horizontal line moves upward, and the vertical line moves leftward; in the upper left Pacman, the horizontal line moves downward, and the vertical edge moves leftward, etc.). So, if the context is determined by the local information (like an extended line), then the motion runs orthogonal to the strip; if the context is determined by the overall shape, then the motion makes the square rotate.



**Movie 2.** The basic demonstration of the rotating Kanizsa square. When four Pacmen are presented, a rotating illusory square is perceived. When only one of the Pacmen is presented, only the vertical or horizontal shift of the edges or linear motion of the corner in an oblique direction is perceived.

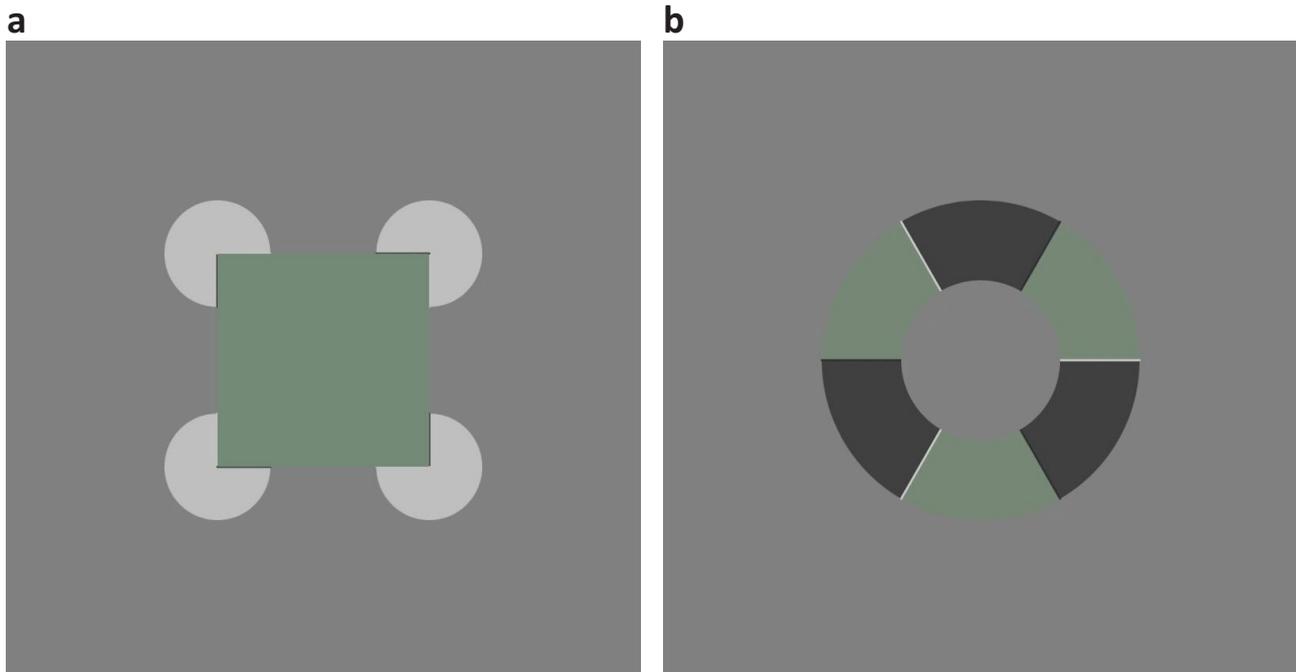
The conflict can be noticed most directly in Movie 2, where square rotates counterclockwise, but if three of the Pacmen are removed, the mouth of the remaining Pacman (i.e. the visual part composing the illusory square) no longer appears to be tilting; rather, the local percept is horizontal and vertical shifts of the two motion strips. It is also probable to perceive a linear motion of the entire corner (the combination of the two orthogonal strips) in the oblique direction, but this motion is not rotational or indicating a tilt. This means that the tilt or rotational motion seen when all four squares are present is an emergent appearance that cannot be seen in any individual elements. Even though the motion of lines inherently allows multiple interpretations of its direction and velocity (aperture problem), the apparent change of its orientation (i.e. what we call rotational motion here) is not included in those inherent multiple interpretations. Flynn and Shapiro (2018) demonstrated that local motion directions can be integrated and modulated by physical shapes, but this modulation could be explained by the aperture problem.

An important scientific contribution of the present work is the finding that the integration of motion signals into rotation can be robustly achieved even with an illusory shape. Indeed, local motion signals can be integrated into rotation with a physical shape (Movie 3a and b). In these movies, since the ‘moving’ components are visually connected, the occurrence of the rotating appearance is more predictable. However, in the illusory shape version, given that the Pacmen are

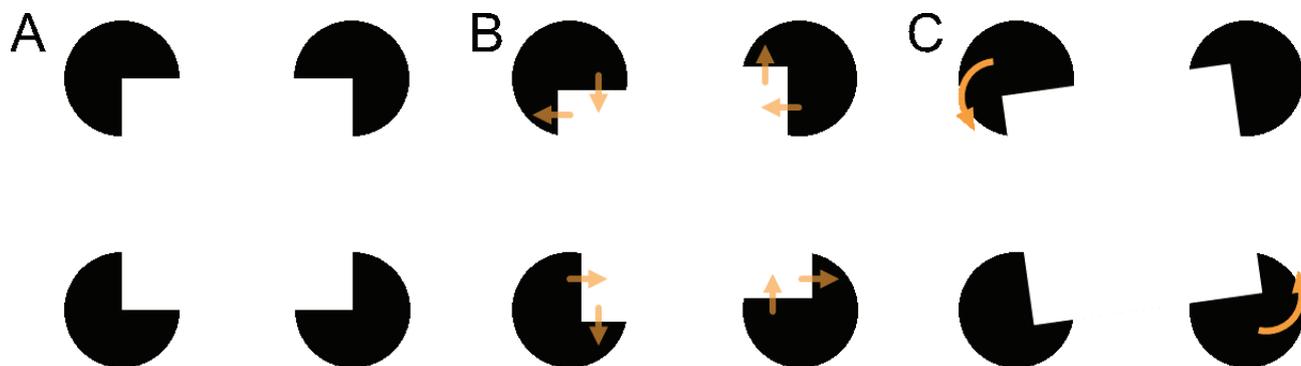
physically isolated, the square would appear to deform (Figure 1A and B, and Movie 2), though it does not. The square actually remains perceptually unified because the observer perceives it as being as rigid as physical ones (Figure 1C). This tendency is evident in Movie 4 as well, where the corners physically move: the vertical edges move left and right, and the horizontal edges move up and down. In this movie, even though there is a physical misalignment of visible edges, the observer perceives a rigid square that rotates back and forth (though in this case, the motion is small and not perpetual). The appearance is consistent with Bradley’s (1987) study, where his observers maintained the perception of the contour even when the physical positions of the visible edges are distorted, suggesting the robustness of perceived contours in the presence of small bottom-up perturbations. The tendency to perceive the square as rigid helps the isolated motion signals to be integrated into the smooth and emergent rotation, and the present work demonstrates the robustness of this tendency.

### Variations

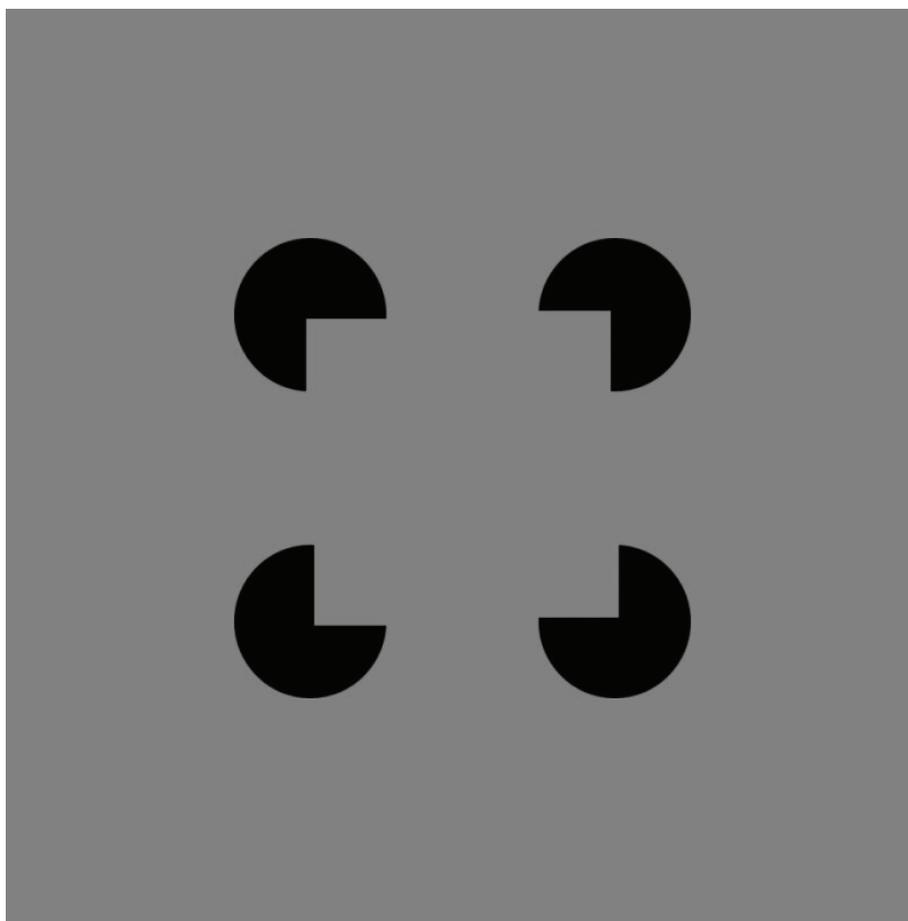
Flynn and Shapiro (2018) demonstrated that the smooth motion produced by luminance modulation is invariant to phase shifts added equally to both strip and its adjoining area. That is, if motion is produced in a rightward direction by a background modulation of phase  $0^\circ$  and strip modulation of phase  $90^\circ$ , then rightward motion will also be produced by adding a phase offset  $\theta^\circ$  to both the background and strip modulations. Hence, the



**Movie 3.** (a) Perpetual rotation of a square with physical contours. (b) Perpetual rotation of a ring.



**Fig. 1.** (A) The physical position of the Kanizsa square. (B) The appearance of the square expected from local motion signals. Since each edge of the Pacman mouths signals a vertical or horizontal shift, deformation is expected to be perceived. (C) The actual appearance of the square (exaggerated for clarity). The square appears to rotate while maintaining its rigid shape, and the edges appear to be tilted.

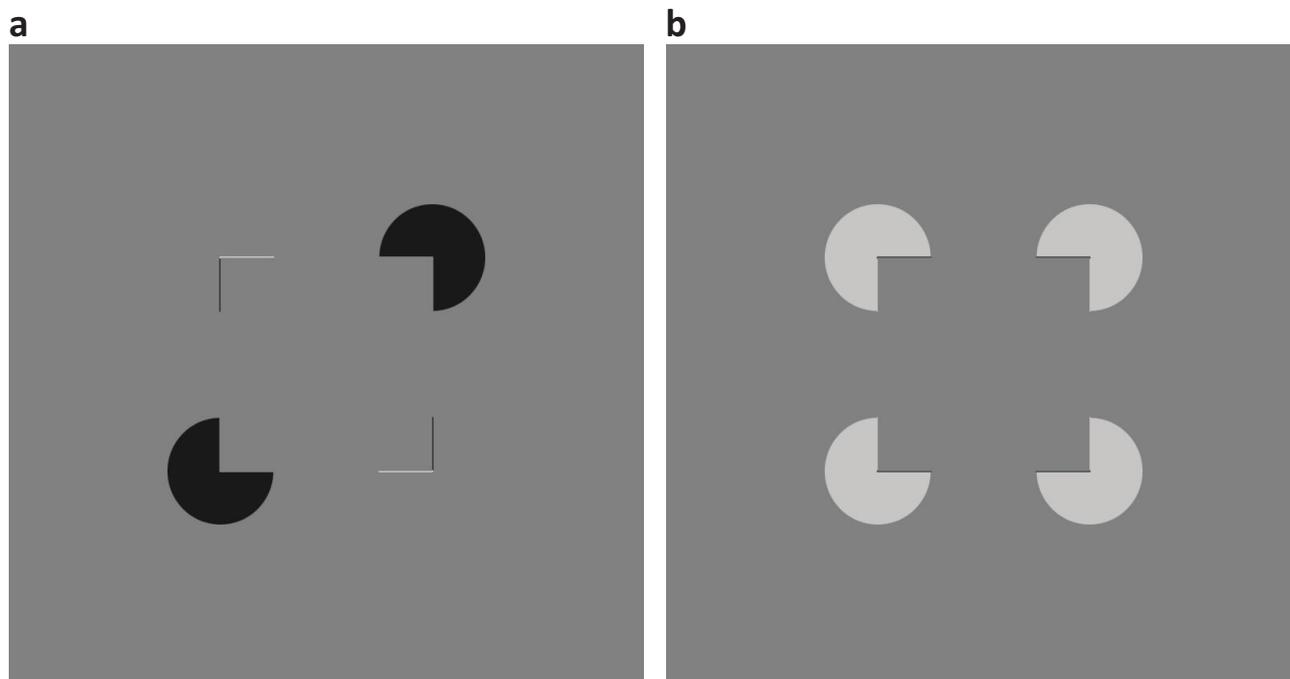


**Movie 4.** Global motion indicated by physical local motions of the Pacmen's mouths. A alternating rigid square is perceived even when the mouths are physically not aligned.

direction of motion is dependent on the phase *difference* between the background and the strip, and not on the 'DC' modulation. As with Flynn and Shapiro (2018), this means that there can be situations where, for instance, one Pacman can be modulating from light to dark, and another Pacman can be modulating from dark to light,

and yet the motion is in the same direction due to the corresponding changes in strip modulation.

In Movie 5a, we shift the phase modulation of the Pacmen so that those in the alternating corners are  $180^\circ$  out of phase with each other. Not surprisingly, the phase shift of two of the Pacmen maintains the same perceived



**Movie 5.** (a) A phase-asynchronized version. The rotating appearance is maintained. (b) A variant version where the speed of the top left and bottom right ‘Pacmen’ was modulated to give a faster illusory motion signal than the other corners. The apparent rotation becomes less smooth.

global motion as in Movie 1a. In Movie 5b, the modulation frequency of two Pacmen and the corresponding strips is doubled. In this case, the frequency-doubled strips/Pacmen seem to move faster than the non-frequency-doubled strips/Pacmen, and this motion distorts the shape of the global figure (i.e. the square).

Movie 5b, therefore, shows the limitation of the observer’s tendency to perceive rigidity. In Movie 5b, there is a recognizable shape, but that shape is not perceived as rigid since two corners move faster than the other two corners. So, while the phase does not have to be synchronized among the corners for smooth rotation (Movie 5a), the difference in velocity among them has an impact on the perception of rigid shapes.

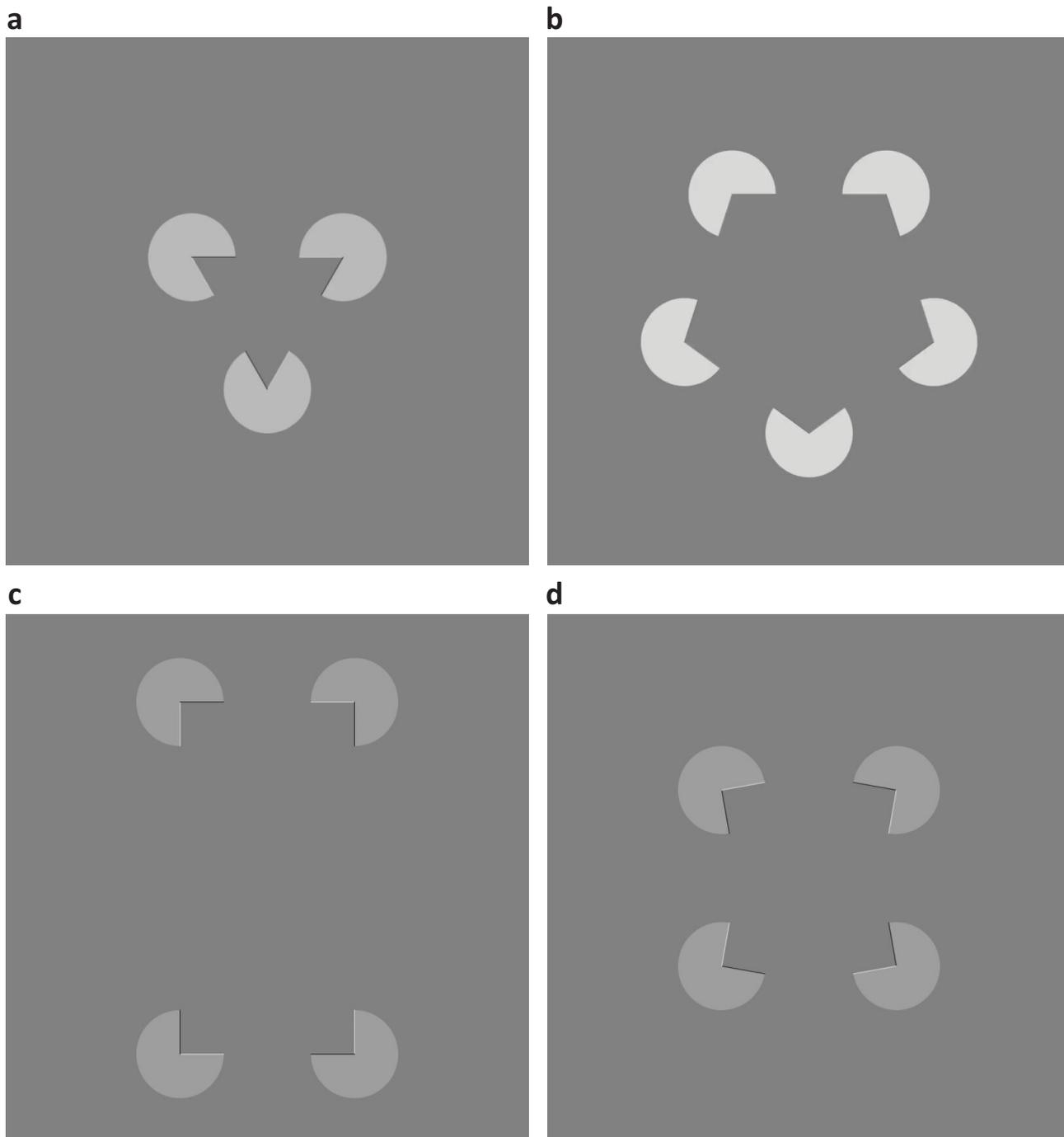
We also present the effects with a varying number of Pacmen. In Movie 6a and b, an illusory triangle (A) and pentagon (B) appear to rotate counterclockwise. As might be expected, the motion of the global shape becomes smoother with more vertices since there are additional sources of motion information. Still, in both movies, the perception of the global shape does not eliminate the perception of local elements. For instance, in Movie 6b, the motion of the global pentagonal shape is strong, but with attention to the Pacmen, the observer can notice the linear motion of the vertex (the intersection of the strips) or individual shifts of each strip.

When the central shapes are extended to produce variations of the four-sided shape, like the rectangle in Movie 6c, the appearance of deformation seems to be

slightly enhanced, presumably because the direction of each local motion signal is slightly different from what would be expected for an actual rotation of a rectangle (i.e. when a vertical rectangle rotates, each vertex should move to, for example, west-northwest or west-southwest, not northwest or southwest). Similarly, with a ‘thin’ figure with an hourglass-like shape (Gold et al., 2000; Nagai et al., 2008), the deformation appearance is dominant (Movie 6d). Previous studies report that illusory contours are also robustly perceived in those figures (Gold et al., 2000; Nagai et al., 2008), but the contradiction of motion direction seems critical for the rotation perception.

It is also possible to combine elements to create competing global shapes. The ‘gear illusion’ in Movie 7a shows two Kanizsa squares, as in Figure 1; the square in the upper right spins counterclockwise, and the square in the bottom left spins clockwise. The bottom left corner of the right square and the upper right corner of the left square also belong to the central cross-shaped ‘gear’. When the gear ‘spins’ counterclockwise, the motion is consistent with the motion of the bottom left square but in conflict with the motion of the right square, and vice versa when the gear spins clockwise. The figure is therefore locally consistent in that there are motion edges that produce consistent shapes, but globally impossible since the motion of the two squares cannot occur at the same time.

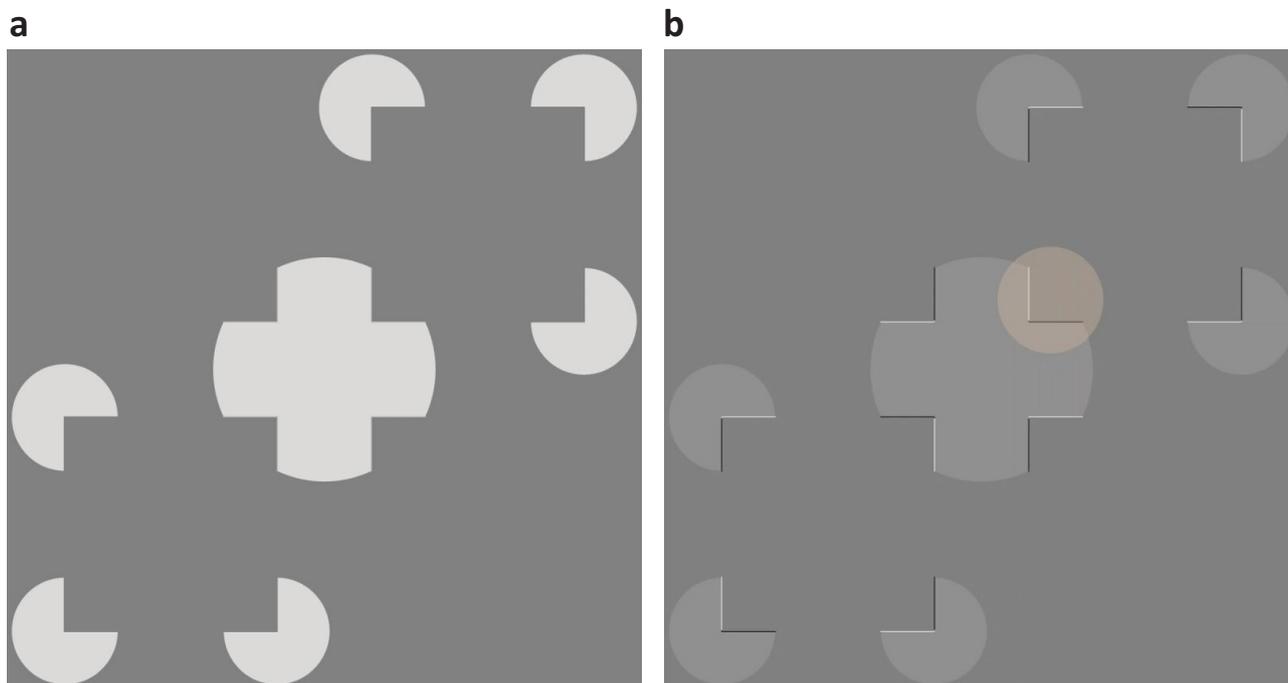
The display is therefore a motion analog of other well-known figures with global inconsistencies (e.g. Penrose’s triangle or Impossible Trident). It is worth noting what



**Movie 6.** (a) A triangle version. The deformation appearance is stronger than in the square version. (b) A pentagon version. The rotation appears smoother than in the square version. (c) A rectangle version. (d) An hourglass-like figure version.

happens when the motions of the squares and gear switch from consistent to conflicting with each other. At the level of the local information, that is the edges, the motion switches from moving from left to moving right and from moving up to moving down. At the level of the global shape, the motion switches from a rotating square when consistent with the gear, to a rotation in which one edge stops (as if it is being squished). While the display's appearance is not

unexpected, the display is of interest for two reasons: (1) The speed at which the visual system adjusts to the different global motions (edge shifts direction, and the global story is created almost instantly); and (2) The gear never changes in response to the square. The gear always appears to rotate clockwise or counterclockwise and never shifts its appearance to align with the motion of the square. It is as if the gear always has ownership of the edge.



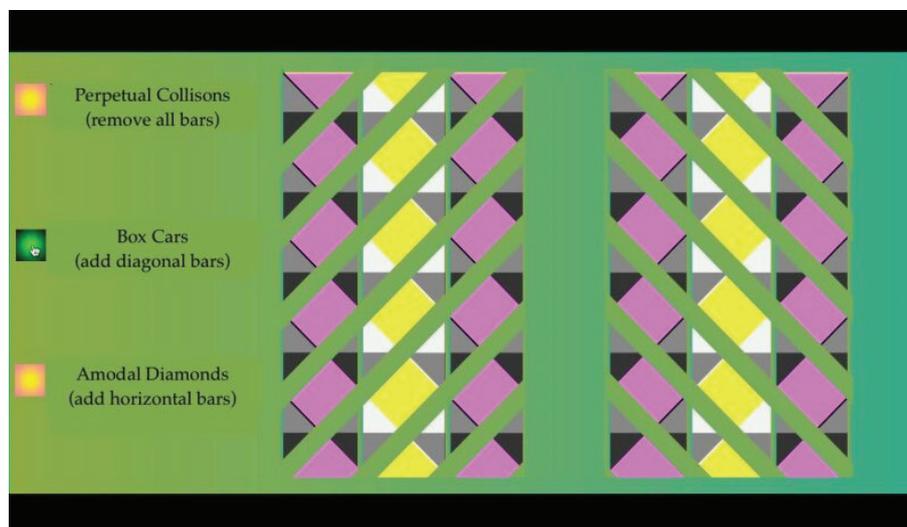
**Movie 7.** (a) The top illusory square appears to rotate counterclockwise and the bottom square clockwise. The central ‘gear’ (cross) is switched twice to be either constant with the top or the bottom square. The ‘gear’ always moves consistently with its apparent motion. The squares sometimes have a corner, which has the opposite motion signal to its other three corners. When opposite, it goes on moving in the same direction as its other corners so being an impossible figure. (b) Another version of the gear illusion. The corner indicated by the orangish circle appears to be tilted to either left or right, depending on whether the observer attends to the top right Kanizsa square or the central gear shape.

In Movie 7b, another version of the gear illusion, two Kanizsa squares are rotating in the same direction, and the gear is rotating in the opposite direction; therefore, there is no conflict of rotations. An interesting part of this movie is in the corner shared by the top right square and the central gear (indicated by an orangish circle). When observers attend to the top right Kanizsa square, this corner appears to be slightly tilted to the left, in accordance with the top right square’s rotation (i.e. the horizontal edge appears to rise rightward). However, when observers attend to the central gear, this corner appears to tilt to the right, in accordance with the gear’s rotation (i.e. the horizontal edge appears to descend rightward). The same phenomenon also occurs in the other shared corner. Those shared corners have two possible patterns of illusory tilt, and they can be switched by top-down attention. This demonstrates that the perception of local information can be modulated by what it is perceived to compose, and this should be considered as another instance of duo-nature figures, which allow for two conflicting interpretations.

The effects of contradictory motion and inferences about shapes can also be seen in the perpetual collision illusion (Movie 8). The illusion was presented at the 2008 Best Illusion of the Year contest, by Arthur Shapiro and Emily Knight, but has not been published. The display consists of columns of colored diamonds (a pink column,

yellow column, pink column, presented twice). The area between the colored diamonds is made up of four achromatic spinning diamonds. The spinning diamonds are divided into four quadrants: two grey quadrants, one bright quadrant, and one dark quadrant; one of the gray quadrants has a black edge, and the other gray quadrant has a white edge (this is the same pattern as in Long-Range Argyles, Flynn & Shapiro, 2014). When the achromatic area spins, the edges that meet the colored diamonds follow the same color contrast pattern that produces motion in the illusions shown here (and were derived from Shapiro et al., 2005). The main effect is that even though the colored columns are physically stationary, the yellow columns appear to drift to the left, and the pink columns appear to drift to the right. The motion is perpetual – the pink and yellow columns are always headed toward each other (or away from each other), but they never meet (and they never grow farther apart). The motion occurs because the rotation of the squares generates a pattern of color change at the edges, and that pattern is similar to the pattern generated by the sinewave modulation in Movie 1a.

Movie 8 also shows the illusion with bars covering up opposite sides of the diamonds. We refer to this as the boxcar illusion because the colored fields appear to move at 45° (or -45°) angles, as if they were boxcars moving up



*Movie 8.* The perpetual collision illusion (Shapiro & Knight, 2008).

or down a hill. The crucial observation is that the oblique motion is always present but perceptually ‘disappears’ when the occluding bars are removed. That is, the uphill cars move at  $45^\circ$ , but the addition of edges that move in the  $-45^\circ$  direction makes the shape move horizontally ( $0^\circ$ ); it is as if the visual system either computes the vector sum of the  $45^\circ$  and  $-45^\circ$  signals or creates a conditional estimate of the most likely motion direction. In either case, the addition of local motion signals at  $-45^\circ$  removes the possible interpretation of  $45^\circ$  motion. The same argument could be made for the downhill cars moving at  $-45^\circ$ .

Finally, Movie 8 also shows a condition where a bar is placed horizontally across the display. In this display, the corners of the diamonds are covered, and, therefore, there is no motion signal in the center of the colored diamonds. The shapes appear as diamonds that drift horizontally behind the bars. We refer to this version of the effect as the amodal diamonds illusion since the diamonds appear to be ‘completed’ behind the overlaying bars. The horizontal motion suggests that the direction of motion follows the perceptual completion of the shape, since a vector sum at the top and bottom corners would generate vertical motion.

### Discussion

Demonstrations of Gestalt principles typically show that global perception cannot be predicted by qualities of the local elements (i.e. whole greater than sum of parts). Considerable effort has been spent trying to understand how global percepts can be constructed from local elements, with explanations ranging from the application of Gestalt laws (e.g. Pomerantz & Portillo, 2011), to inferences and Bayesian estimations based on mid-level processing (Feldman, 2001), and to machine-learning algorithms that generate objects (Lonnqvist et al., 2023).

Less effort has been devoted to trying to understand the ‘duo-organization’ (Boring, 1936) of object creation, where observers can switch between local and global percepts at their own volition. Shapiro (2021) and Shapiro and Hedjar (2019) have been working with the idea that illusions are best understood in terms of perceptual conflicts similar to the duo-organization discussed by the early gestalt theorists. In this approach, our perception of reality is the result of a ‘reality engine’ (Hoffman, 2010) or ‘voting process’ (Hawkins, 2021) that binds together the brain’s neural subprocesses that process limited aspects of the potential information. Illusions may arise when the reality engine (or voting process) is unable to integrate conflicting neural processes into a single story or because there are multiple perceptual stories that seem incompatible with each other. Here, the local and global percepts are akin to different perceptual modes that seem to be created from a conflict in how the reality engine weights the different visual processes.

Our demonstrations are based on the organization of ‘motion strips’. The curious – and most general – finding of these demonstrations is that while individual motion edges move linearly in a direction that is perceived as orthogonal to the edge or oblique when viewed in isolation, those edges when part of a group tend to rotate as a global shape. Such effects of global information on the perception of local parts have been reported by several studies (Adelson, 1993, 2000; Gilchrist & Annan, 2002; Hock & Nichols, 2012). The rotational appearance cannot solely be explained by the inherent ambiguity of line motion (i.e. the aperture problem), as the local motion alone, regardless of its interpreted direction, cannot indicate curved motion or changes in edge orientation.

The capture of local motion by the global motion may be typical for objects in the natural world. For instance,

each point on the circumference of a rotating circle moves in a different direction than the shape's motion. In our demonstrations, however, the local elements can be identified easily, and an observer can switch between local elements and the global elements, as if the display was a bistable image. The emergent rotation of a global shape and its bistable appearance are underpinned by the finding that the illusory shape is perceived to be as rigid as physical shapes. Motion signals might cause an appearance of the shape's deformation, but the perceptual rigidity of the illusory shape does not allow it and does integrate them as physical shapes do. This feature enables global rotation to emerge while the elements are isolated and easily identifiable. Indeed, the rotating appearance can be created even with physical shapes (Movie 3a and b), but local motion is less perceivable in this case.

The illusions shown here, though different from each other in their effect, also show that the local changes are resolved primarily through focal attention, and the global perception creates the appearance of a rotating shape. The ability to switch between the percepts suggests that the encoding for global and local elements is always present, and the grouped perception is just one possible interpretation. In some respects, this difference between global and local responses has similarities to other motion illusions based on perceptual conflicts, such as the double drift/curveball illusion (Lisi & Cavanagh, 2015; Shapiro et al., 2010; Tse & Hsieh, 2006), where a circle moves vertically from the top to the bottom of the screen (global motion), while internal motion moves horizontally (local motion). The conflict between local and global motion is resolved differently in central vision, which can represent both sources of information (the spin and the drop) vs. peripheral vision, which combines the vertical as well as the horizontal motions (the ball appears to drop diagonally). While the global shape moves in a different direction of motion than the local motion, it is not based on the linear combination of two different directions, as in the double drift illusion.

The present paper added a new instance of the 'whole' containing more information than the mere sum of its elements. It is composed of a classic illusory contour but gives rise to emergent motion. It is characterized by the bistable appearance of motion and demonstrates the visual system's robust tendency to perceive shape rigidity. The bistable perception and the tendency for rigidity have been relatively underexplored in the history of vision science. The present demonstrations provide a valuable foundation for future investigations into these intriguing phenomena.

### Note

Generative AI was used in the preparation of an early draft to locate incorrect English sentence structure and suggest corrections.

### Conflict of interest and funding

This study was supported by the Japan Society for the Promotion of Science (grant number: 22K13878).

### References

- Adelson, E. H. (1993). Perceptual organization and the judgment of brightness. *Science*, *262*(5142), 2042–2044. doi: 10.1126/science.8266102
- Adelson, E. H. (2000). Lightness perception and lightness illusions. In M. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 339–351). MIT Press.
- Anderson, B. L. (2020). Mid-level vision. *Current Biology: CB*, *30*(3), R105–R109. doi: 10.1016/j.cub.2019.11.088
- Anstis, S. M., & Rogers, B. J. (1975). Illusory reversal of visual depth and movement during changes of contrast. *Vision Research*, *15*, 957–961. doi: 10.1016/0042-6989(75)90236-9
- Boring, E. G. (1936). Koffka's principles of Gestalt psychology [Review of the book *Principles of Gestalt psychology*, by K. Koffka]. *Psychological Bulletin*, *33*(1), 59–69. doi: 10.1037/h0053346
- Bradley, D. R. (1987). Cognitive contours and perceptual organization. In S. Petry & G. E. Meyer (Eds.), *The perception of illusory contours* (pp. 201–212). Springer.
- Feldman, J. (2001). Bayesian contour integration. *Perception & Psychophysics*, *63*(7), 1171–1182. doi: 10.3758/BF03194532
- Feldman, J. (2015). Bayesian models of perceptual organization. In J. Wagemans (Ed.), *The Oxford handbook of perceptual organization* (pp. 1008–1026). Oxford University Press.
- Flynn, O., & Shapiro, A. (2014). A note concerning the relationship between the Adelson's Argyle illusion and Cornsweet edges. *Psihologija*, *47*(3), 353–358. doi: 10.2298/PSI1403353F
- Flynn, O. J., & Shapiro, A. G. (2018). The perpetual diamond: Contrast reversals along thin edges create the appearance of motion in objects. *i-Perception*, *9*(6), 204166951881570. doi: 10.1177/2041669518815708
- Froyen, V., Feldman, J., & Singh, M. (2015). Bayesian hierarchical grouping: Perceptual grouping as mixture estimation. *Psychological Review*, *122*(4), 575–597. doi: 10.1037/a0039540
- Geisler, W. S., & Kersten, D. (2002). Illusions, perception and Bayes. *Nature Neuroscience*, *5*(6), 508–510. doi: 10.1038/nn0602-508
- Gilchrist, A. L., & Annan, V. (2002). Articulation effects in lightness: Historical background and theoretical implications. *Perception*, *31*(2), 141–150. doi: 10.1068/p04sp
- Gold, J. M., Murray, R. F., Bennett, P. J., & Sekuler, A. B. (2000). Deriving behavioural receptive fields for visually completed contours. *Current Biology*, *10*(11), 663–666. doi: 10.1016/S0960-9822(00)00523-6
- Gregory, R. L., & Heard, P. F. (1983). Visual dissociations of movement, position, and stereo depth: Some phenomenal phenomena. *Quarterly Journal of Experimental Psychology A*, *35*(Pt 1), 217–237. doi: 10.1080/14640748308402127
- Hawkins, J. (2021). *A thousand brains: A new theory of intelligence*. Basic Books.
- Hock, H. S., & Nichols, D. F. (2012). Motion perception induced by dynamic grouping: A probe for the compositional structure of objects. *Vision Research*, *59*, 45–63. doi: 10.1016/j.visres.2011.11.015
- Hoffman, D. D. (2010). *Human vision as a reality engine*. Foundation for the Advancement of Behavioral and Brain Sciences. Retrieved from <https://sites.socsci.uci.edu/~ddhoff/HoffmanFABBS.pdf>

- Jagarikin (2023, October 2). Not moving. (in Japanese) [X post]. X. Retrieved from <https://x.com/jagarikin/status/1708601401545576952>
- Kanizsa, G. (1976). Subjective contours. *Scientific American*, 234(4), 48–52. doi: 10.1038/scientificamerican0476-48
- Katz, D. (1935). *The world of colour*. Kegan Paul.
- Kitaoka, A. (2006). Configurational coincidence among six phenomena: A comment on van Lier and Csathó (2006). *Perception*, 35(6), 799–806. doi: 10.1068/p5319b
- Koffka, K. (1935). *Principles of Gestalt psychology*. Harcourt, Brace.
- Lisi, M., & Cavanagh, P. (2015). Dissociation between the perceptual and saccadic localization of moving objects. *Current Biology: CB*, 25(19), 2535–2540. doi: 10.1016/j.cub.2015.08.021
- Lonnqvist, B., Wu, Z., & Herzog, M. H. (2023). Latent noise segmentation: How neural noise leads to the emergence of segmentation and grouping. arXiv. <http://arxiv.org/abs/2309.16515>
- Mather, G., & Murdoch, L. (1999). Second-order processing of four-stroke apparent motion. *Vision Research*, 39(10), 1795–1802. doi: 10.1016/s0042-6989(98)00191-6
- Murakami, I. (2004). The aperture problem in egocentric motion. *Trends in Neurosciences*, 27(4), 174–177. doi: 10.1016/j.tins.2004.01.009
- Nagai, M., Bennett, P. J., & Sekuler, A. B. (2008). Exploration of vertical bias in perceptual completion of illusory contours: Threshold measures and response classification. *Journal of Vision*, 8(7), 25.1–17. doi: 10.1167/8.7.25
- Pomerantz, J. R., & Portillo, M. C. (2011). Grouping and emergent features in vision: Toward a theory of basic Gestalts. *Journal of Experimental Psychology: Human Perception and Performance*, 37(5), 1331–1349. doi: 10.1037/a0024330
- Shapiro, A. G. (2021). Hybrid motion illusions as examples of perceptual conflict. *Journal of Illusion*, 2, 7084. doi: 10.47691/joi.v2.7084
- Shapiro, A. G., Charles, J. P., & Shear-Heyman, M. (2005). Visual illusions based on single-field contrast asynchronies. *Journal of Vision*, 5(10), 764–782. doi: 10.1167/5.10.2
- Shapiro, A. G., & Hedjar, L. (2019). Color illusion as a spatial binding problem. *Current Opinion in Behavioral Sciences*, 30, 149–155. doi: 10.1016/j.cobeha.2019.08.004
- Shapiro, A. G. & Knight, E. (2008). Perpetual collisions. Retrieved from <https://illusionoftheyear.com/2008/05/perpetual-collisions/>
- Shapiro, A., Lu, Z. L., Huang, C. B., Knight, E., & Ennis, R. (2010). Transitions between central and peripheral vision create spatial/temporal distortions: A hypothesis concerning the perceived break of the curveball. *PLoS One*, 5(10), e13296. doi: 10.1371/journal.pone.0013296
- Steinman, R. M., Pizlo, Z., & Pizlo, F. J. (2000). Phi is not beta, and why Wertheimer's discovery launched the Gestalt revolution. *Vision Research*, 40(17), 2257–2264. doi: 10.1016/s0042-6989(00)00086-9
- Stiny, G. (2006). *SHAPE: Talking about seeing and doing*. MIT Press.
- Stumpf, P. (1911). Über die Abhängigkeit der visuellen Bewegungsempfindung und ihres negativen Nachbildes von den Reizvorgängen auf der Netzhaut. *Zeitschrift für Psychologie*, 59, 321–330.
- Todorović, D. (1996). A Gem from the Past: Pleikart Stumpf's (1911) Anticipation of the Aperture Problem, Reichardt Detectors, and Perceived Motion Loss at Equiluminance. *Perception*, 25(10), 1235–1242. doi: 10.1068/p251235
- Tse, P. U., & Hsieh, P. J. (2006). The infinite regress illusion reveals faulty integration of local and global motion signals. *Vision Research*, 46(22), 3881–3885. doi: 10.1016/j.visres.2006.06.010
- Wallach, H. (1935). Über visuell wahrgenommene Bewegungsrichtung. *Psychologische Forschung*, 20(1), 325–380.
- Wertheimer, M. (2012). Experimental studies on seeing motion. (M. Wertheimer & K. W. Watkins, Trans.). In L. Spillmann (Ed.), *On perceived motion and figural organization* (pp. 1–91). MIT Press. (Original work published in 1912).
- Wuerger, S., Shapley, R., & Rubin, N. (1996). “On the visually perceived direction of motion” by Hans Wallach: 60 years later. *Perception*, 25(11), 1317–1367. doi: 10.1068/p251317