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PHENOMENAL REPORT

Hybrid motion illusions as examples of perceptual conflict

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Abstract

Shapiro and Hedjar (2019) proposed a shift in the definition of *illusion*, from 'differences between perception and reality' to '*conflicts* between possible constructions of reality'. This paper builds on this idea by presenting a series of motion hybrid images that juxtapose fine scale contrast (high spatial frequency content) with coarse scale contrast-generated motion (low spatial frequency content). As is the case for static hybrid images, under normal viewing conditions the fine scale contrast determines the perception of motion hybrid images; however, if the motion hybrid image is blurred or viewed from a distance, the perception is determined by the coarse scale contrast. The fine scale contrast therefore masks the perception of motion (and sometimes depth) produced by the coarser scale contrast. Since the unblurred movies contain both fine and coarse scale contrast information, but the blurred movies contain only coarse scale contrast information, cells in the brain that respond to low spatial frequencies *should* respond equally to both blurred and unblurred movies. Since people undoubtedly differ in the optics of their eyes and most likely in the neural processes that resolve conflict across scales, the paper suggests that motion hybrid images illustrate trade-offs between spatial scales that are important for understanding individual differences in perceptions of the natural world.

Keywords: *Illusion*; *blur*; *motion*; *spatial scale*; *hybrid images*; *philosophy of reality*; *modes of perception*

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Introduction

The role of visual illusions in understanding perception has become a prominent topic in vision science (Braddick, 2018; Fermuller, 2017; Purves, Wojtach, & Lotto, 2017; Rogers, 2019; Todorović, 2018; Van Buren & Scholl, 2018). The term *illusion* is problematic because, as noted by Koenderink (2017), its definition depends on how a person views the relationship between perception and reality (that is, one's 'ontological convictions'). For instance, if one holds that our perception corresponds to an objective factual world, then illusions can be understood as a misperception or erroneous interpretation of reality. From this point of view, illusions exist because perception deviates from measurements of the physical world (Todorović, 2020), or the term is superfluous because illusory misperceptions can be shown to correspond to ecologically relevant information (Rogers, 2017, 2019) or empirically determined aspects of the physical world (Purves et al., 2017). If, on the other hand, one starts from the ontological position that our perception is a 'controlled hallucination' produced by the brain (Hoffman et al., 2015; Koenderink, 2010; Seth, 2019), then the term *illusion* is problematic because our perceptions can never be exact copies of reality (see Boring, 1942; Hochberg, 1964; Hoffman, 2019; James, 1890), and *all* our perceptions are to some extent illusory.

Shapiro and Hedjar (2019) proposed a possible way around this ontological conundrum by suggesting that illusions are best understood in terms of perceptual conflicts – an idea that has a long history in the philosophical literature (see Burnyeat, 1981; Westphal, 2005). That is, similar to the controlled hallucination position, what we perceive as reality is the result of a 'reality engine' (Hoffman, 2010) or 'voting process' (Hawkins, 2021) that binds together the

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brain's neural subprocesses. For healthy brains, the reality engine (or Hawkins' voting process) is usually able to construct a single coherent story that is both a practical description of the external world and so convincing that it seems interchangeable with reality itself (Crick, 1994). Illusions arise when the reality engine (or voting process) has difficulty creating a single coherent story of the world, either because it is unable to integrate conflicting neural processes into a single story or because there are multiple perceptual stories that seem incompatible with each other.

Shapiro and Hedjar's (2019) intention, then, is to shift the definition of *illusion* from 'differences between perception and reality' to '*conflicts* between possible constructions of reality'. Most of the illusions from my laboratory, and the illusions in this paper, have been generated – intentionally – by creating conflict *across stimulus dimensions*. For instance, the contrast asynchrony illusion (Shapiro, 2008; Shapiro, Charles, & Shear-Heyman, 2005) juxtaposes luminance information modulated synchronously and contrast information modulated asynchronously; the visual system resolves the conflict by creating the paradoxical perception that lights modulate in antiphase, but still become light and dark at the same time. Another example, the double drift/curveball illusion (Gurnsey & Biard, 2012; Kwon, Tadin, & Knill, 2015; Lisi & Cavanagh, 2015; Shapiro, Lu, Huang, Knight, & Ennis, 2010; Tse & Hsieh, 2006), creates conflict between two sorts of motion: a circle moves vertically from the top to the bottom of the screen while internal motion moves horizontally inside the circle. Conflict in the double drift illusion is resolved differently in the central visual system, which can represent both sources of information (the spinning ball appears to drop vertically), and the peripheral system, which combines the vertical as well as the horizontal motion (the ball appears to drop diagonally).

Hybrid illusions can be interpreted with reference to the illusion-as-conflict framework because they juxtapose near-range contrast (often thought of as contrast at an edge, or spatially fine contrast, or high spatial frequency content) with longer-range contrast (that is, contrast that goes across edges, or spatially coarse contrast, or low spatial frequency content). Well-known static hybrid images are the Monroe-Einstein illusion (Oliva & Schyns, 2017; Oliva, Torralba, & Schyns, 2006), in which a high-frequency Albert Einstein is combined with a low-frequency Marilyn Monroe; photo-tiled images such as Harmon Faces (Harmon & Julesz, 1973), where blocked portraits of famous individuals are easily discernible when viewed from a distance, but not from up close; hidden images (Wade, 2017), where fine high-contrast lines mask low-frequency images; the pointillism of Seurat (Foa, 2015); and the fragmented images of Chuck Close (Pelli, 1999).

As a rule, the visual system resolves the conflict produced by hybrid images by extracting the highest spatial frequency object: that is, if spatially fine contrast is visible, the observer perceives the high spatial frequency content portion of the hybrid image, but if those details are removed (by blur, or by viewing the object from a distance), the perception – as if by magic – switches to the low spatial frequency content of the hybrid image. To illustrate this point, Fig. 1 (an image from my lab that has been shown in my talks since 2008) juxtaposes near-range and longer-range contrast, and is typically perceived as a pattern of diamonds against a blurry background. If the image is blurred by squinting, by blurring with a lens, by viewing from a distance, or by removing glasses (if the observer needs glasses to correct their vision), then the image (rather dramatically) shifts to squares, not unlike the pattern in Norcia's Coffer Illusion (Norcia, 2006). It is worth emphasising that blur does not add information, but instead removes high spatial frequency content. In other words, the unblurred image contains both near-range and longer-range contrast (i.e. high and low spatial frequency content), whereas the blurred image contains only longer-range contrast (i.e. just the low spatial frequency content). In principle, then, cells in the brain that respond to low spatial frequency content should respond equally to both blurred and unblurred versions of the images.

In this paper, I present a series of *motion* hybrid illusions, which have the same underlying principles as their

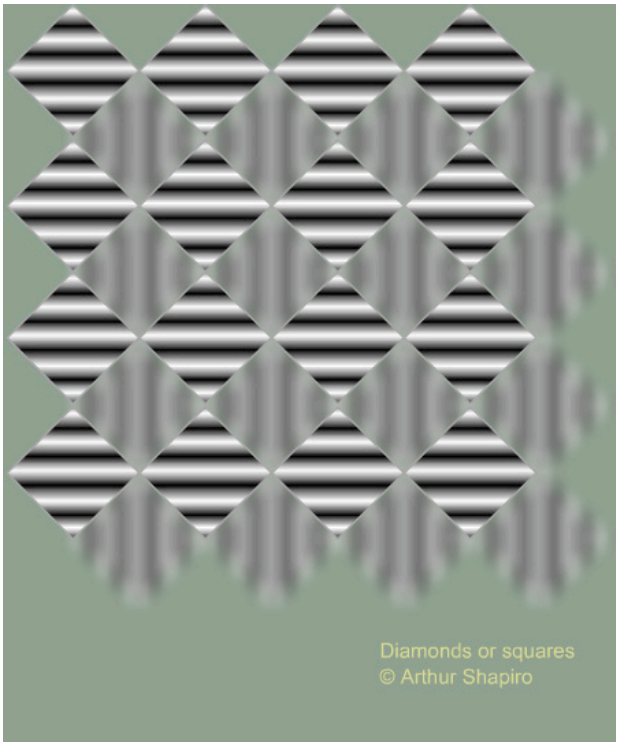

Fig. 1. An example of a static hybrid image. When viewed directly, the image appears as diamonds on a blurry background; when blurred by squinting or optics, the image appears as squares.

static counterparts but, when blurred, produce the experience of motion and, sometimes, changes in depth. Motion hybrid illusions illustrate what can be referred to as the ‘spatial frequency binding problem’ (Burge, Rodriguez-Lopez, & Dorronsoro, 2019): under normal viewing conditions, the visual system is always confronted with information at different spatial scales, and the reality engine has to figure out how to construct a story that combines some of this information and discards other information. The stories conveyed through low spatial frequency information are often very different from the stories conveyed through high spatial frequency information; as a result, the switch from one scale to another can yield radically different percepts. In the discussion, I will highlight how these motion hybrid illusions may be important for understanding individual differences in perception, for people with normal or corrected visual acuity, and also for patients with clinical eye disorders.

Where has all the motion gone?

The motion hybrid illusion shown in Movies 1a, 1b, and 1c examines contrast in what Shapiro and Knight (2008) refer to as a luminance gauge configuration (individual frames of the movies are shown in Fig. 2; some of the illusions were originally part of the Best Illusion of the Year Contest [Shapiro & Knight, 2007]). The display consists of a thin vertical bar shaded from dark on the bottom to bright on the top, surrounded by an achromatic field. As in a standard brightness illusion (Blakeslee & McCourt, 2013; McCourt & Blakeslee, 2017), the bar’s appearance depends on the luminance of the surrounding field: if the field is mid-luminance (Fig. 2a), the top half of the gradient bar looks light, and the bottom half looks dark; if the luminance of the field is decreased (Fig. 2b), the location of dark/light transition on the bar moves lower; and if the luminance of the field is increased (Fig. 2c), the location of the light/dark transition moves higher.

The display is referred to as a luminance gauge because the dark-light transition represents where the luminance contrast between the surrounding field and the bar is minimal. The transition can therefore be used to read the luminance of the surrounding field as if it were a gauge, and the luminance gauge can be used to investigate temporal aspects of contrast by modulating the luminance of the background sinusoidally in time, and observing how the light/dark transition point moves up and down the bar.

The insertion of a blocker bar that separates the bar from the surround eliminates the perception of motion at the dark/light transition. In Fig. 2d, a still image of the blocker bar is shaded orthogonal to the shading of the internal bar (bright yellow to dark blue). The effects of the blocker bar can be seen in Movie 1a at time mark 0:44, and an abbreviated version can be seen in Movie 1b.

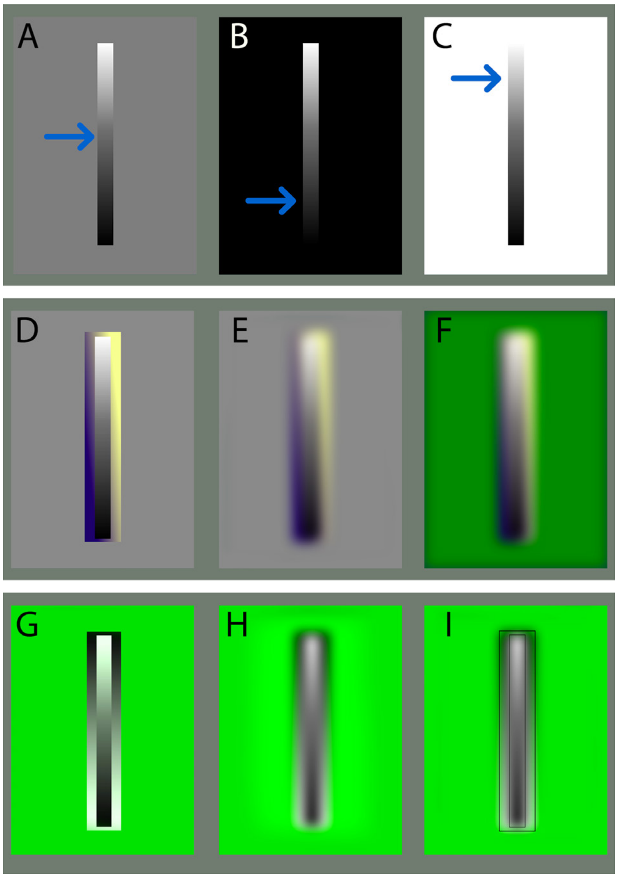

Fig. 2. Motion hybrid illusion based on Shapiro and Knight (2008). The images in Fig. 2 are screen stills from Movies 1a, b, and c. Motion is visible in blurred versions of movies but not in unblurred versions. Panels a, b, and c depict a luminance gauge, in which a gradient bar is placed on a uniform background. If the luminance background is modulated in time, the transition between light and dark shifts up and down. (d) The action of the transition point can be eliminated with the blocker bar. (e) Blurring the image from 2d produces motion not visible in the unblurred image. (f) The effect depends on luminance and hue. (g and h) Similar effects, but with a different shading to the blocker bar. (i) The perception of the low frequency motion can be greatly reduced by the addition of thin black lines.

The blocker bar suggests that an observer’s perception depends only on the contrast at the edges between the bar and surround; however, when the image is blurred, the bar appears to shift up and down at a slightly oblique angle (Figs. 2e and 2f; Movie 1a, time mark 1:02; Movie 1b, time mark 0:05). So, even though it seems as if our perception is controlled by the local contrast between the bar and surround, the visual system still encodes contrast at greater distances, but this contrast perceptually registers when the image is unblurred.

Movie 1c (single frame in Figs. 2g and 2h) shows the same principle but with a blocker bar that has vertical shading opposite the centre (bright on bottom, dark on top). Here the surround field modulates in time from dark green to bright green, showing that the effect depends on luminance, not on hue comparisons. When unblurred, the centre bar does not change; when blurred, the bar and blocker bar have a contorted motion, switching between a narrow top and wide bottom to a wide top and a narrow bottom. Shapiro and Knight (2008) show a similar image with a central bar modulation and gradient background.

Movie 1c also shows that the addition of thin black lines (Fig. 2i) greatly diminishes the motion in the blurred version of the illusion. The finding suggests that the addition of local contrast decreases the perceptual consequences of longer-range contrast. One could speculate that this is due to the weighting of contrast information, but it could also be the consequence of object perception. The encoding of an object requires the selection of frequency information at the spatial scale of the object, and the filtering out of spatial frequency content lower than the size of an object. The addition of black lines, therefore, could be considered to be a new object of a narrow size, which would lead to a decrease in the selection of lower spatial frequency information.

Blur creates depth

If the configuration from Movie 1, Fig. 2, is repeated, then the number of sources of contrast increases: local contrast between surround and edges, some longer-range contrast between surround and non-contiguous bars, and an even longer-range contrast across individual configurations. Presumably, since the contrast at the edges overrides the perceptual effects of the long-range contrast, it would do the same for even longer-range contrast.

In Movie 2 (single frames shown in Figs. 3a and 3b), the configuration from the previous section is repeated 18 times (three rows of six). The phases of the modulating backgrounds are offset from each other so as to create a motion signal drifting from left to right across each row. As in Movie 1 and Fig. 2, unblurred viewing shows no

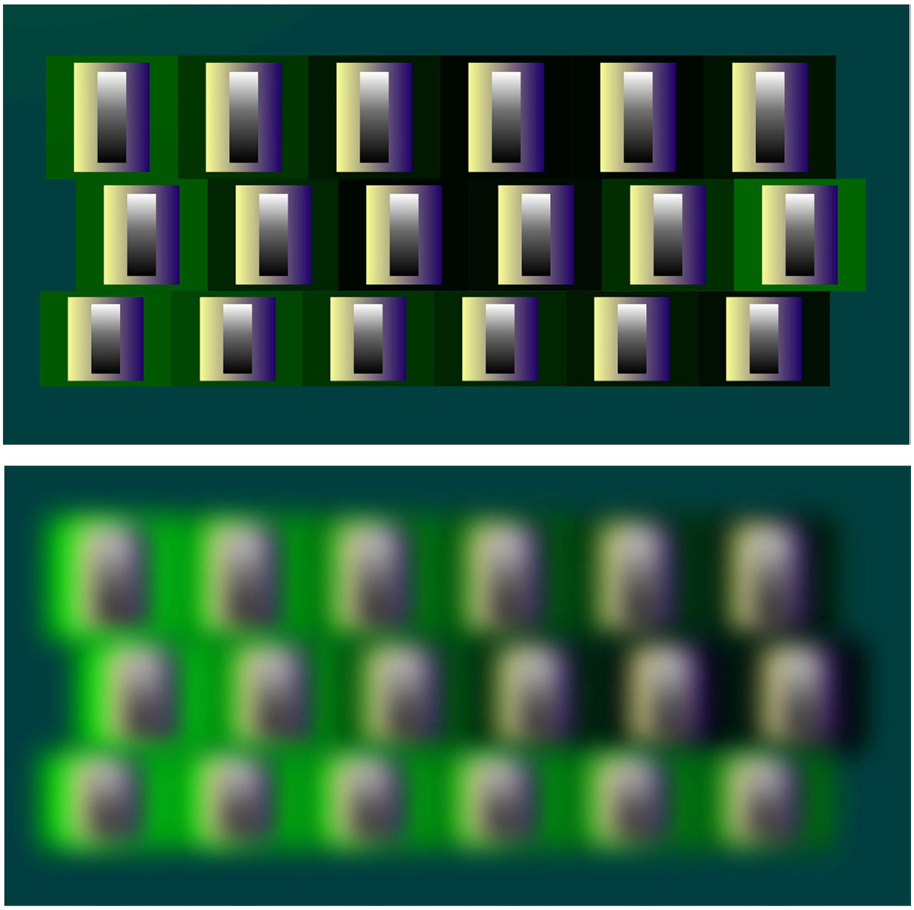

Fig. 3. Illusion corresponds to Movie 2. The configuration of an element similar to Fig. 2d repeated 18 times (three rows of six), thereby creating additional sources of contrast. The luminance modulation levels of the background elements are offset from each other, creating a luminance (i.e. first-order) motion signal that moves from left to right. In the unblurred movie (a), the first-order motion is visible, but elements do not appear to move. In the blurred version of the movie, the elements drift from side to side, and appear to change in depth.

change in appearance of the centre bars; however, the motion that arises from the phase shift across the elements remains visible, indicating that the contrast edges eliminate contrast-generated motion, but not standard first-order motion.

The blurred version of the image creates a substantial see-saw effect; the motion moves both horizontally and in the depth plane. Local contrast therefore seems to eliminate the perceptual contribution of long-range contrast, but here the long-range contrast contributes to the perception of motion (as in Movie 1 and Fig. 2), and also to the perception of depth. It is likely that the addition of depth is due to blur itself, and due to the combination of contrast motion and the luminance motion across the elements.

Rotation illusions: It is still, yet it moves

The effect of blur is also evident in conditions where individual motion elements are chained to create a large global motion perception. For instance, Movie 3 shows two rings composed of 12 ovals (Fig. 4 shows still frames from the movie in four different conditions). Each oval is divided into two halves whose luminance shifts in time from light to dark. The curved line is non-essential, but seems to produce slightly more effective motion than a straight line. If the luminance modulations are out of phase with each other, a motion signal is created that makes the ring appear to rotate even though the ellipses are physically stationary. The phase of the inner ring is configured so that the motion energy produced by each element is in the clockwise direction; for the outer ring, the motion energy is in the anti-clockwise direction. Each oval is surrounded by a thick white border to add to the high frequency contrast.

Under normal viewing conditions, people with good acuity see the luminance alternation of each of the rings, but they do not see the rings rotating. However, if the rings are blurred, the perception of motion becomes very strong:

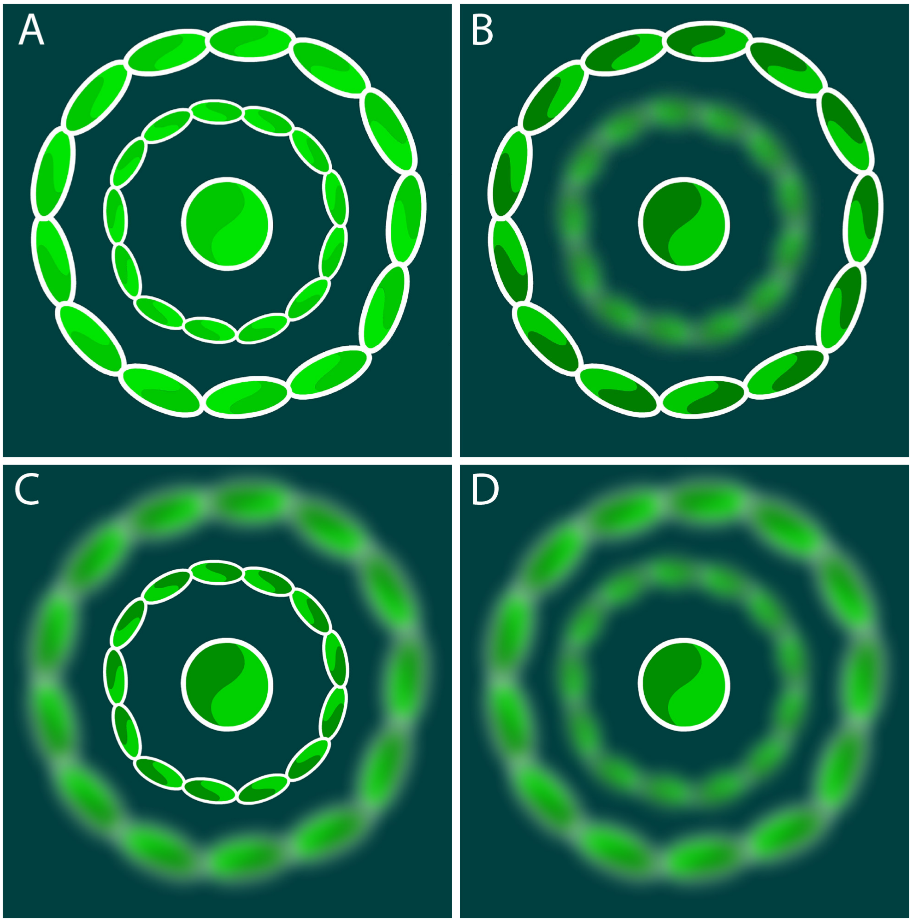

Fig. 4. This figure shows individual frames from Movie 3. Two rings composed of 12 ovals; each oval is divided into two halves whose luminance shifts in time from light to dark. The phase of each oval is offset so as to create local motion energy. The motion energy is consistent with a ring that moves clockwise or anticlockwise even though the elements are stationary. (a) When the image is unblurred, the motion is not visible. (b) When the inner ring is blurred, the inner ring rotates, but not the outer ring. (c) When the outer ring is blurred, the outer ring rotates, but not the inner ring. (d) When both are blurred, both rings appear to move.

the inner ring moves clockwise, and the outer ring moves anti-clockwise. In Movie 3a, the inner and outer rings are blurred individually, as shown in Fig. 4b, where the inner ring is blurred and the outer ring is unblurred; in Fig. 4c, where the inner ring is unblurred and the outer ring is blurred; and in Fig. 4d, where both rings are blurred (the blur is digital, but the same effect can be created with optics). The advantage of blurring the rings separately is that the effect is most evident when the rings are contrasted with each other. Again, the effect shows that the low spatial frequency content is always present, but it is visible only when the high spatial frequency content is removed through blur.

The blurred motion depends on the phase offset between the elements. Movies 4a and 4b systematically vary the phase of the elements with 30-degree steps (single frames shown in Figs. 5a and 5b). The motion in the blurred display disappears when the phases of the two halves are equal, but is present otherwise (albeit to a greater or lesser degree), and with different phenomenological aspects. A systematic empirical investigation of this type of motion would be worth undertaking.

Near- and far-edge flicker motion

There has been considerable interest on the internet about ‘flicker motion’, where alternation in the luminance of elements creates perpetual motion in one direction (Flynn & Shapiro, 2018). These motion illusions have their roots in Reverse Phi (Anstis, 1970; Anstis & Rogers, 1975; Rogers et al., 2019). To create hybrid motion from this paradigm, I juxtapose flicker for thin edges moving in one direction with flicker for thick edges moving in the opposite direction. These illusions were originally presented at the Best Illusion of the Year contest (Shapiro & Flynn, 2014). As with the previous illusions, under the unblurred condition, observers perceive motion consistent with the near-edge contrast, but in the blurred condition, observers see motion consistent with the far-edge contrast. It should be noted that this illusion, unlike the previous demonstrations, requires the observer to blur the image on their own; the effect seems to be more sensitive to observer’s distance, acuity, and size of display.

The illusions are shown in Movies 5a, b, and c; stills from the movies can be seen in Figs. 6a, b, and c. Each movie consists of an array of elements (28x4 in a, and 9x12 in b and c). The temporal spatial arrangement of each element is shown as an X, t plot in Fig. 6d. Each element consists of four thin bars that change luminance over time. The luminance of the outer elements modulates at phase 0, the luminance of one bar is at phase 90, and the luminance of the other bar is at phase -90. The two lower panels show the effects of filtering each time slice of the plot: the left X,t plot shows a low spatial frequency filter; the right X,t plot shows a high spatial frequency filter. The filtered images create diagonal bands indicating the direction of motion. The lines in the low spatial frequency filtered image tilt to the left; the lines in the high spatial frequency filtered image tilt to the right. The different scales produce motion in opposite directions; furthermore, since the bands in the low spatial frequency filtered image are steeper than the bands in the high spatial frequency filtered image, the blurred image should appear to be moving faster than the unblurred image.

In Movies 5a and b, the centre elements flicker so as to create motion in the opposite direction compared to the elements on the edges of the array. The effect therefore is to create centre motion that moves in one direction, and surround motion that moves in the other. If the display is blurred, then the motion of each of the elements reverses direction and moves faster (consistent with the motion shown in the X,t plots). Movie 5c (corresponding to Fig. 6c) has

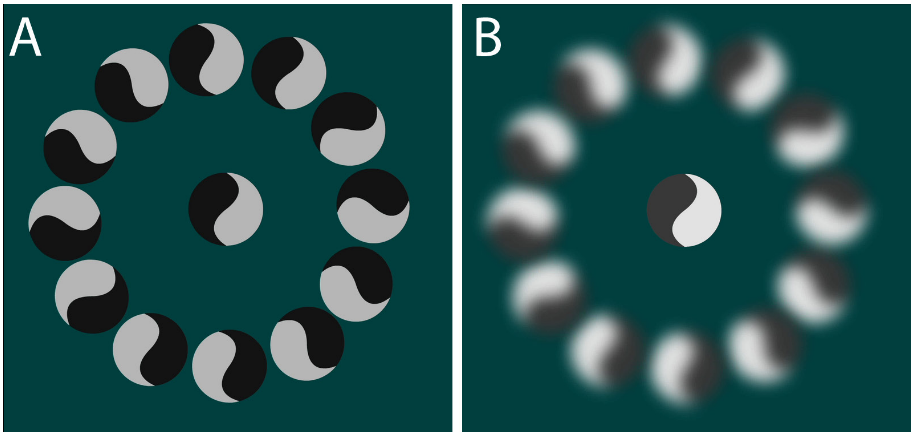

Fig. 5. Images from Movies 4a and 4b. Both movies show a similar configuration to Movie 3. Twelve elements divided in two; the luminance of each half element changes in time. The movies show the effects of parametrically shifting the phase of the elements in 30 degree steps (-180 degrees, to 180 degrees). The motion is not visible in the unblurred condition (a) but is visible for most phases in the blurred condition (b).

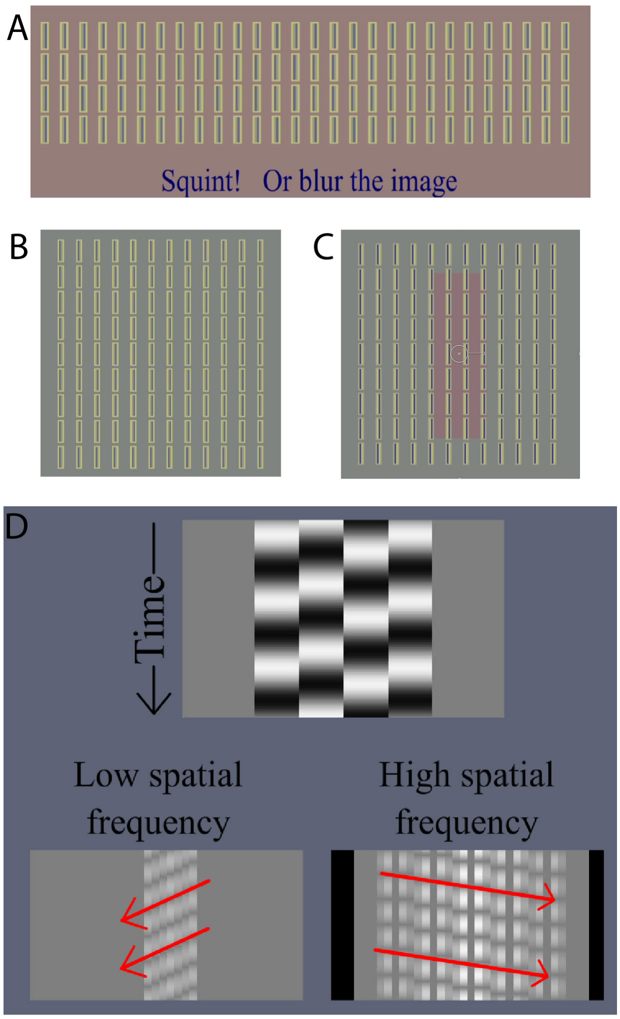

Fig. 6. a–c show still frames from Movies 5 a, b, and c. The alternation in the luminance contrast of elements creates perpetual motion in one direction. The elements contain a surround field, so that near range contrast is in one direction, and longer range contrast is in the other. In a and b, motion that reverses when the movie is blurred is shown. (c) shows that blurred, but not unblurred motion can lead to motion capture. (d) shows the flicker of the elements as an X-t plot, and how filtering at different scales can produce motion in different directions.

a low contrast rectangular bar in the middle of the display. The bar seems to move along with the elements when the movie is blurred, but not when the movie is unblurred. The low spatial frequency motion is therefore capable of 'capturing' a stationary low contrast rectangle placed in the centre of the screen. Of note is that the rectangle is captured by motion when the low spatial frequency motion is visible even though the low spatial frequency information is always present. For this effect in particular, there seems to be notable variance across observers.

This illusion is consistent with the illusions in the previous sections except that there are two motion signals (short-range contrast in one direction, and longer-range contrast in the other). The long-range contrast is invisible when high spatial frequency content edges are present. Blur allows us to perceive the previously invisible long-range contrast. The effect is unusual because, most often, the visual system has no difficulty perceiving two different motions at the same time (see, for instance, the colour wagon wheel or double drift when viewed centrally); however, in this movie, one motion signal renders the other motion signal invisible. It is possible that longer range motion is invisible because the two motion signals are both contrast-generated, are in opposite directions, and are in the same location; but this is a hypothesis that needs further investigation.

Discussion

The motion hybrid illusions shown here fall primarily in the domain of mid-level vision. Mid-level vision consists of the complementary processes of *analysis*, where the optic array is decomposed into its informational components, and *synthesis*, where the components are recomposed into meaningful structures (Anderson, 2020). In the unblurred versions of motion hybrid illusions, the presence of both low and high spatial frequency information permits a synthesis into a meaningful structure in which there is no motion (or motion in one direction). In the blurred versions, the mid-level synthesis can no longer use the high frequency information, and the displays suddenly appear to contain motion (in opposite directions). The important point, therefore, is that synthesis into meaningful structures is such a powerful process that motion information at low spatial frequency can be rendered invisible.

Of course, the removal of low spatial frequency motion information is necessary for us to create a meaningful perception of the world. Our eyes and bodies are constantly in motion, and the image on the retina is therefore similar to taking a picture with an unsteady or moving camera; mid-level processes that accentuate objects share some commonalities with processes that decrease the effects of motion blur. In addition to Harmon and Julesz (1973), Oliva et al. (2006), and Oliva and Schyns (2017), many investigators have examined the processes for integrating edge information or aligning phase information (for instance, Del Viva & Morrone, 1998; Henriksson, Hyvärinen, & Vanni, 2009; May & Georgeson, 2007; Morrone & Burr, 1997; Watt & Morgan, 1985). Such processes are most likely related to how the visual system adapts to blur (Elliott, Georgeson, & Webster, 2011; Webster, Georgeson, & Webster, 2002), and to processes that accentuate the presence of high spatial frequency edges even after the edges have visually disappeared (Brady & Oliva, 2012).

It is intuitively plausible that the synthesis process underlying mid-level vision selectively excludes low spatial frequency information, since it is not that informative about the details of an object. This is not to say that low spatial frequency information is unimportant. The Sinha laboratory has demonstrations of the robustness of low spatial frequency vision for face detection (Gilad-Gutnick & Sinha, 2017), and has shown the importance of low spatial frequency content for healthy visual development (Vogelsang et al., 2018). Graphic designers talk about the 'squint test', which asks artists to view their work by squinting so as to access the overall layout of the design. My laboratory has been arguing that both low and high spatial frequency colour are important because each spatial scale conveys different information about the environment (Shapiro, Hedjar, Dixon, & Kitaoka, 2018; Shapley, Nunez, & Gordon, 2019), and that differences in how mid-level vision filters lower spatial frequency colour may be responsible for inter-observer variation in the colour-changing dress (Dixon & Shapiro, 2017).

An understanding of individual differences in low spatial frequency response may prove to be clinically important. As a human with presbyopia, I have become aware that people with imperfect vision encounter low frequency motion on a regular basis, but people with good acuity tend not to notice this motion. Here is a (not so) hypothetical anecdote: A 50-year-old, presbyopic vision scientist notices a distracting blurry motion while driving; he asks his teenage son in the passenger seat if he sees the motion. The son, who has better acuity, doesn't see the motion and stares incredulously at his father with a tinge of worry around his eyes. Who, then, is to be believed, the presbyopic older person or the younger person whose vision is typically more reliable?

Such conflict across observers has the potential to lead to troubling miscommunications. Ophthalmologists often comment about patients who complain about seeing distracting illusory motion at low light levels, and while driving. The assumption is that imperfect optics produces some endogenous image, or there is some form of optical or neural problem that creates mistaken responses. It could be, however, that the patients are seeing information that is actually in the environment, which others with 'better' vision cannot perceive. One can only imagine the issues that this may cause for people with conditions where questions of personal reality are already at the forefront (such as patients with dementia and Alzheimer's), if their visual acuity is compromised.

Motion

Most of the demonstrations in the paper show motion across stationary elements that alternate contrast in various ways. The presence of motion in these conditions is simple to explain with standard first-order motion models (Adelson & Bergen, 1985; Lu & Sperling, 2001). Flynn (2016, dissertation) was able to account for a wide range of data with Challinor and Mather's (2010) motion energy model, simply by changing the value of one parameter concerned with spatial scale. However, Rogers et al. (2019) noted that 'attributing the reversed motion effects to motion energy models is not an explanation, but a description of what happens when these particular stimuli provide the input to a particular motion energy model'. They propose that motion energy models predict reversed apparent motion effects because the models incorporate spatial smoothing, and that any realistic motion model that incorporates spatial smoothing will signal reversed phi motion. Indeed, other motion models not based on motion energy, such as Fermuller (2017) and Hock, Schöner and Gilroy (2009), would almost certainly be able to account for the presence of motion from flickering contrast.

The blurred images also create curious phenomena in addition to motion. For instance, Fig. 3 and Movie 2 show that blur can also reveal changes in depth. Movie 2 is different from the others in that it combines low spatial contrast with motion across each element (a first-order motion). The first-order motion remains visible even when unblurred, which indicates that contrast at the edges suppresses some types of motion, but not others. This shouldn't be surprising since there are numerous occasions in which two types of motion are visible (see the colour wagon wheel illusion, for instance). The perception of depth in Movie 2 may therefore arise from the combination of the first-order motion and the contrast motion, and this combined motion is only visible when the display is blurred. This hypothesis requires empirical and systematic investigation, but is related to possible explanations of other phenomena that suggest that a combination of first- and second-order motion can lead to odd phenomena (Shapiro, Knight, & Lu 2011), and may be consistent with other explanations (Gurnsey & Biard, 2012; Kwon et al., 2015; Lisi & Cavanagh, 2015; Shapiro et al., 2010; Tse & Hsieh, 2006).

Additionally, my laboratory has recently published a motion hybrid illusion that is related to the Pulfrich effect, referred to as the Helix illusion. For that illusion, a three-dimensional helix appears as a two-dimensional pattern that drifts up or down when it is blurred or made achromatic. Shapiro and LoPrete (2020) have shown empirically that even minimal contrast in a single element can override a two-dimensional percept and replace it with three-dimensional rotation. Lastly, we note that in Figure 1, squinting seems to match the contrast of the diamond; the change produced by blur, therefore, seems to affect the shape as well as the brightness of the object. Similar colour changes seem to occur for the motion hybrid images, but might be hard to address with a small number of observers in a laboratory, particularly since there seems to be notable variance across observers.

Relation to the definition of 'illusion'

Shapiro and Hedjar (2019) have proposed a framework for discussing illusions based on *conflicts* between possible constructions of reality. As stated in the introduction, the aim is to shift the definition of *illusion* from 'differences between perception and reality' to '*conflicts* between possible constructions of reality'. The motion hybrid illusions shown here, like their static counterparts, create conflict *across stimulus dimensions* by juxtaposing low and high frequency information.

Conflicts that create illusions can occur at a number of different levels. Conflicts can occur *across modalities*: for instance, a stick in water looks bent but appears straight to the sense of touch, but only one can be telling the truth (see Ayer, 1940/1964). Conflicts can occur *across observers*, as in the colour-changing dress, where one observer sees blue-black, while another sees white-gold; such conflicts are fundamental to our understanding about the social construction of reality (Gilchrist, 2015). Conflicts can occur *across representations:* for instance, in Kitaoka's Rotating Snakes (Kitaoka, 2003, 2017), one representation holds that the image is stationary, while another holds that the image is moving.

As Shapiro and Hedjar (2019) noted, illusions are always defined by a comparison: a line that looks bent is only an illusion in comparison to another representation in which the line is thought to be straight. Similarly, brightness/lightness displays aren't illusions because identical patches of light look different from each other; they are illusions because the display with mismatched luminance levels stands in contrast to other conditions in which objects don't change brightness when they move in front of a variegated background (Whittle, 2003). So, even though a reasonable explanation (or, as is often the case, many reasonable explanations) may account for why lines look bent, or patches look different, the displays are still illusory because the brain's reality engine (or the 1,000 brains voting process) has difficulty creating a single story.

The illusion-as-conflict framework has practical implications: it is possible to generate illusions by juxtaposing information across stimulus dimensions, and then observing how our perception system resolves the conflict. Information in the visual array varies along multiple dimensions (Adelson & Bergen, 1991); hence, there are plenty of possibilities for the creation of such illusions. Direct psychophysical investigations along any of these dimensions are time-consuming procedures, and often difficult to perform. Investigations across dimensions become combinatorically more difficult, particularly when one considers adaptation, contrast along each dimension, response levels, and the certainty of individual differences when dimensions are combined. Phenomena created by comparing across dimensions may therefore offer the opportunity to gain insight into such processes, and how they differ from one person to another.

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