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Perceiving-the-present and a systematization of illusions

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Abstract

Over the history of the study of visual perception there has been great success at discovering countless visual illusions. There has been less success in organizing the overwhelming variety of illusions into empirical generalizations (much less explaining them all via a unifying theory). Here we show that it is possible to systematically organize more than 50 kinds of illusion into a 7 by 4 matrix of 28 classes. In particular, we demonstrate that (1) smaller sizes, (2) slower speeds, (3) greater luminance contrast, (4) farther distance, (5) lower eccentricity, (6) greater proximity to the vanishing point, and (7) greater proximity to the focus of expansion all tend to have similar perceptual effects, namely to (A) increase perceived size, (B) increase perceived speed, (C) decrease perceived luminance contrast, and (D) decrease perceived distance. The detection of these empirical regularities was motivated by a hypothesis, called “perceiving-the-present”, that the visual system possesses mechanisms for compensating neural delay during forward motion, and we show how this hypothesis predicts the empirical regularity.

1. Introduction

Visual illusions serve as important pieces of evidence for motivating and testing hypotheses about the visual system, and as is true for evidence generally, visual illusions become more useful when empirical regularities can be identified (analogous to realizing that an empirical plot closely follows a straight line). Although an enormous assortment of visual illusions have been discovered over the history of the visual perception literature, there has been comparatively less success at identifying empirical generalizations that describe the great menagerie of illusions (although see Coren et al., 1976). In Section 3 we describe our main result, which is an empirical generalization we have uncovered that organizes on the order of 50 illusions into a six by four matrix of 24 illusion classes. The 24 illusion classes concern the

effects of (1) size, (2) speed, (3) luminance contrast, (4) distance, (5) eccentricity, and (6) vanishing point, respectively, on perceived (A) size, (B) speed, (C) luminance contrast, and (D) distance. (Four more classes will also be discussed, making 28 classes in all.) Before presenting this empirical generalization, we first, in Section 2, describe how the result was motivated by a “perceiving-the-present” hypothesis that the visual system possesses mechanisms for attempting to compensate for appreciable neural delays between retinal stimulation and the elicited percept during forward motion.

2. Motivation behind the empirical generalization: Perceiving-the-present

In this section—amounting to the first half of this paper—we introduce the perceiving-the-present hypothesis, briefly review how it has been used to explain many classical geometrical illusions, and describe how it predicts a new empirical regularity, the regularity which we discuss in the Section 3 and is the main result of this paper. We believe the empirical generalization and systematization of illusions of Section 3 is a more fundamental and important result than our theoretical claim in this section that perceiving-the-present explains the result. Although the empirical regularity we describe in Section 3 was found by us because of the theoretical motivation discussed in this section, one might reject our hypothesis altogether (or, more weakly, believe the evidence is currently not warranted for accepting it), but accept that the empirical generalization is in need of explanation.

2.1. Perceiving-the-present

Computation necessarily takes time, and because visual perceptions require complex computations, it is not surprising to learn that there is an appreciable latency—on the order of 100 msec—between the time of the retinal stimulus and the time of the elicited perception (Lennie, 1981; Maunsell & Gibson, 1992; Schmolesky, Wang, Hanes, Thompson, Leutger, Schall & Leventhal, 1998). Neural delays of this size are significant, for an observer can move a distance of 10 cm in that time even at a relatively slow walk. Or consider reaching out to grab a one-meter distant object translating in front of an observer at one meter/sec; if an observer did not have perceptual compensation mechanisms, then by the

time he perceives the object, the object will be roughly six degrees displaced from its perceived position, making it nearly impossible to plan and execute appropriate behavioral reaching for a catch. It is therefore reasonable to expect that the visual system will have been selected to have compensation mechanisms by which it is able to, via using the stimulus occurring at time t , generate a perception at time $t+100$ msec that is probably representative of the scene as it is at time $t+100$ msec. In short, we should expect that visual systems have been selected to “perceive the present”, rather to perceive the recent past. Such a perceiving-the-present framework has, in fact, been proposed by Ramachandran and Anstis (1990) and De Valois and De Valois (1991) for motion-capture-related misperceptions of projected location, by Nijhawan (1994, 1997, 2001, 2002), Berry, Brivanlou, Jordan and Meister (1999), Sheth, Nijhawan and Shimojo (2000), Schlag, Cai, Dorfman, Mohempour and Schlag-Rey (2000), and Khurana, Watanabe and Nijhawan (2000) for the flash-lag and related illusions (although there is a debate around this explanation of the flash-lag effect, see citations in Changizi, 2002), and by Changizi (2001, 2003) and Changizi and Widders (2002) for the classical geometrical illusions.

Making specific predictions with the perceiving-the-present hypothesis requires an understanding of how real world scenes tend to change in short periods of time. Given a stimulus at time t , to predict what an observer perceives, we must have some means by which we can say what the probable scene will be at time $t+100$ msec. In particular, since distal properties are typically invariant over short periods of time, we can focus on predicting how projected properties (such as angular size), and also distance properties, tend to change. [See Appendix A for discussion of the distinction between projected and distal properties.] Before introducing the new prediction, we describe how perceiving-the-present has been applied in the past to the classical geometrical illusions; our new prediction is a generalization of that idea.

2.2. Classical Geometrical Illusions

Perceiving-the-present has been brought to bear to account for and unify the classical geometrical illusions (Changizi, 2001, 2003; Changizi & Widders, 2002), such as the Müller-Lyer, double-Judd, Poggendorff, corner, upside-down ‘T’, Hering,

Ponzo, and Orbison (first discovered by Ehrenstein) illusions. The central idea is that the classical geometrical stimuli are similar in kind to the projections observers often receive in a fixation when moving through the world. Furthermore, these projections often possess implicit information as to the probable direction of observer motion. That is, there are ecological regularities such that, given a geometrical stimulus, it is typically the case that the observer is moving toward one region of the stimulus, rather than toward some other region of the stimulus. The perceiving-the-present predicted perceived projection (e.g., perceived angular size, see Appendix A) is not the actual projection, but, instead, the way the probable underlying scene would project in the next moment were the observer moving in the probable direction of motion.

We present here an abbreviated, qualitative version of the argument, and show only how the Hering, Ponzo, and Orbison illusions are accommodated. These stimuli are projections consisting of horizontal or vertical lines placed within a radial display, and may be seen in Fig. 1. Let us first consider the grid in Fig. 1. It is probably due to a real-world grid of horizontal and vertical lines in the observer’s fronto-parallel plane. And now let us consider the radial display. Converging lines provide a strong cue that the vanishing point is the direction of observer motion. Said another way, when observers typically receive projections of converging lines, they are in motion toward the vanishing point. There are two underlying reasons for this. The first is that in the carpentered worlds we inhabit, observers move down hallways and roads, and the vanishing point of the oblique lines is typically also the observer’s direction of motion. The second is that, when in motion, optic flow engenders radial “smear”, and the radial display may serve to mimic this. The *focus of expansion* of optic flow (i.e., the point on the retina from which everything is flowing outward) is identical to the observer’s direction of motion so long as the observer’s gaze is fixed. If, however, an observer fixates on approaching objects, the focus of expansion will be on the fixated object. So long as forward-moving observers tend to fixate on objects near to the direction of motion—i.e., so long as observers tend to look where they are going, something they appear to do (Wilkie and Wann, 2003)—the focus of expansion will correlate highly with observer direction of motion. (We will discuss

this in more detail later in Subsection 2.4.) Fig. 2a is a photograph of idealized optic flow in a moving car in a carpentered environment (on a bridge), and one may readily see both of these features (i.e., real-world converging contours like the side of the road, *and* optic smear) in the picture. Incidentally, just as “tail lines” indicate trajectory and blurring of moving objects and contours in cartoons, radial lines have been used to indicate forward motion toward the center (see also Geisler, 1999; Geisler, Albrecht, Crane & Stern, 2001; Ross, Badcock and Hayes, 2000; Burr, 2000; Burr and Ross, 2002; Cutting, 2002). Radial lines are, for similar reasons, consistent with *backward* flow, but this is an ecologically rare occurrence, and the more probable interpretation of such lines is forward movement (Lewis & McBeath, 2004). Note that we are not claiming that converging lines are not used as perspective cues to the three dimensional, objective properties of scenes. We are claiming that, in addition, they may provide cues to the probable observer direction of motion. If latency correction mechanisms are elicited when the observer is not moving forward, the costs are much less severe than if latency-correction mechanisms are *not* elicited when the observer *is* moving forward, for in the latter but not the former case, the observer is nearing the objects and veridically perceiving them is crucial.

In Fig. 1, then, the observer is probably moving toward the center of the radial display, and is thereby getting closer to the “grid-wall” in the observer’s fronto-parallel plane. We are now in a position to predict what an observer will perceive when presented with Fig. 1 as the stimulus: the observer should perceive the grid to project not as it actually does in the stimulus, but as it would project in the next moment were the observer moving toward the center of the radial display. How, in fact, *would* the fronto-parallel grid project toward the eye if the observer moved forward toward the center of the radial display? Consider first what would happen to the two real-world vertical lines on either side of the radial center if you were to move toward the center. Each of these vertical lines would flow outward in your visual field, but the parts along the horizontal meridian would flow out more quickly (imagine walking through a tall cathedral door, where when close to it the sides of the door above you converge toward one another), which accounts for the Hering illusion. Consider now, say, the square just to the right of center, and how its projection would change

as you move toward the center. The square’s left side will project larger than the square’s right side, which accounts for a standard version of the Orbison illusion, and is also a variant of the Ponzo illusion. In short, consistent with perceiving-the-present, observers perceive the grid to project just as it would project in the next moment were the observer moving forward toward the vanishing point. It is illusory because the observer is, in fact, not moving forward at all; typically, however, when an observer receives such a stimulus on the retina, the observer is moving forward, and the resulting percept accords with the actual projection changes, and there is thus no illusion (i.e., perception accords with reality). Many readers may also perceive the grid to be bulging toward the observer at the center, which, as we will see later, is predicted: in the next moment, the center of the grid will be nearer to the observer than the more peripheral regions of the grid.

2.3. Generalization of the “optic flow regularities” idea

For the remainder of this section we present a new prediction of the perceiving-the-present hypothesis. The idea is a generalization of the above “optic flow regularities” idea used to accommodate the classical geometrical illusions. The explanation of the classical geometrical illusions given above required (i) using vanishing point cues in the stimulus to determine the probable observer’s direction of motion, and (ii) working out how the projected sizes of objects in the scene will change in the next moment when the observer moves in that direction, which depends on where the objects are in the visual field relative to the direction of motion (e.g., the Hering lines bow outward in the visual field more quickly at eye level). More generally, we wish to look for (I) cues to the observer’s direction of motion, and (II) the rates at which properties tend to change depending on where they are in the visual field relative to the observer’s direction of motion. In the following two subsections we discuss two kinds of optic flow regularities, concerning (I) and (II) respectively.

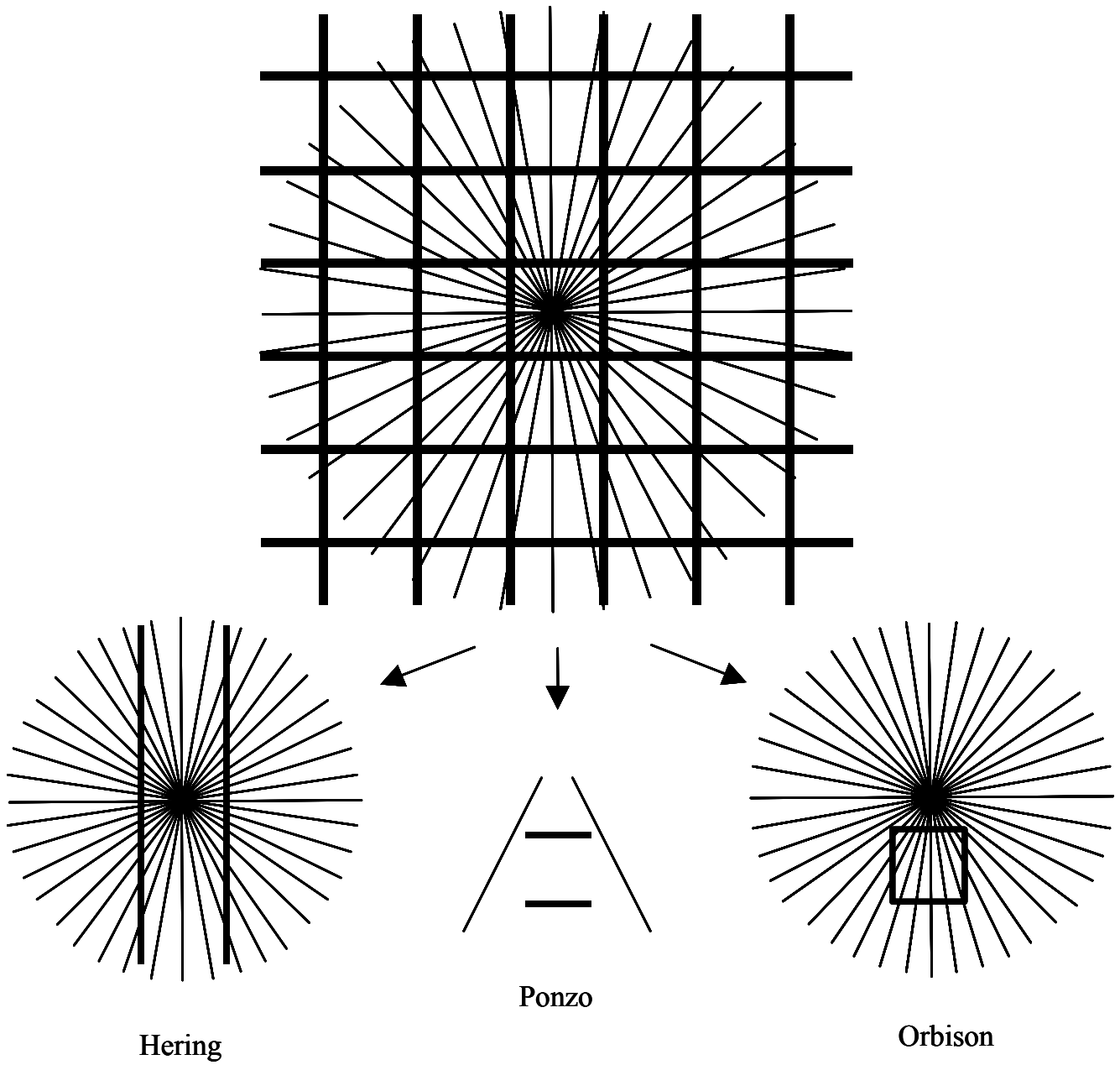


Figure 1

Demonstration of the Hering, Orbison (due originally to Ehrenstein, 1925), and Ponzo illusion. The Hering illusion is exemplified by the perceived curvature of the straight lines. The squares in the grid appear to be distorted, which is the Orbison illusion. And along the horizontal and vertical meridians, the line segments appear longer when closer to the center, which is a version of the Ponzo illusion. These three illusions are also shown by themselves below.

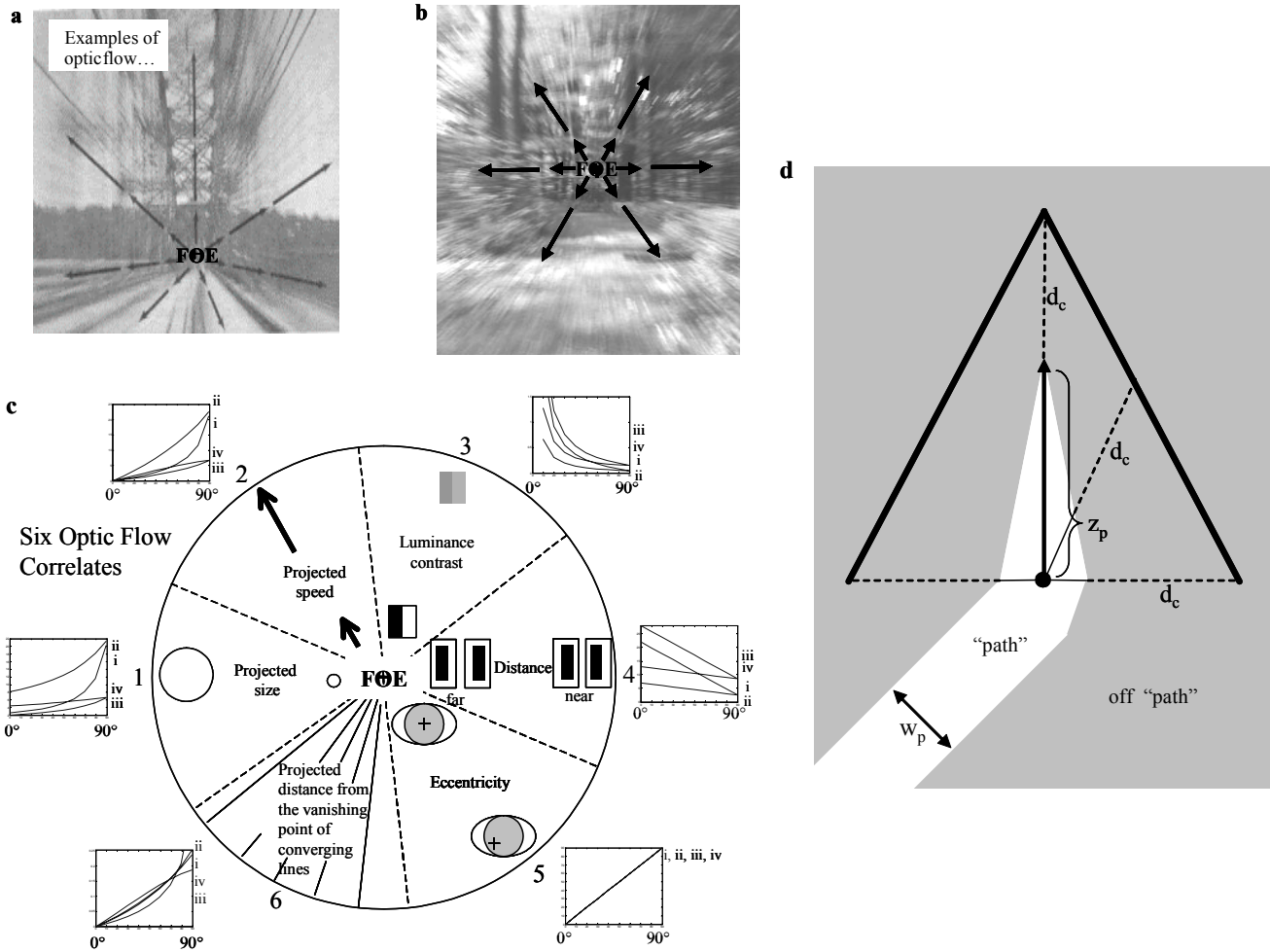


Figure 2

(a) This picture (from the public domain) illustrates many of the correlates of optic flow and the direction of motion. Namely, moving from the direction of motion (the focus of expansion) outwards, projected sizes increase (e.g., the road), projected speeds increase (the arrows), luminance contrasts decrease (notice the overhead structures), distance decreases, and projected distance from the vanishing point of converging lines increases. (b) Another picture (from the public domain), this one of optic flow in a forest. (c) The circle signifies an observer’s visual field, and the center the location of the focus of expansion (FOE), and the observer direction of motion. Around the circle are shown six correlates of optic flow, labeled 1 through 6. For example, correlate 1 is for projected size, and tells us that projected sizes are smaller near the observer direction of motion, and get larger farther from the observer direction of motion. Some of the correlate descriptions need comment. Distance can be cued via many sources of information, but the distance correlate is shown here via using two stereograms, intended for uncrossed viewing: when fused, the one on the left depicts a single black bar behind a rectangular frame (i.e., distance of the black bar is great), and the stereogram on the right depicts a single black bar in front of a frame (i.e., the black bar is near). All but correlate 5, eccentricity, is exemplified by (a) and (b). The eccentricity correlate is due to the fact that observers are typically looking in the direction they are headed, and, in (c), this is signified by an eye with a cross at a location on the retina. Shown next to each correlate is a plot of the average magnitude of the variable (e.g. projected size, projected speed, etc.) as a function of angle from the direction of motion, using the canonical quantitative model in (d). For 6—“projected distance from the vanishing point”—the y-axis in the plot is the probability that an object at that angle from the direction of motion has a sufficiently high projected speed to “induce a smear” on the retina, and thus “create” a converging line whose vanishing point correlates with the direction of motion, we assume here that the probability is proportional to the average projected speed. The four curves in each plot (in some cases overlapping), denoted as i, ii, iii, and iv, are for four settings of the two parameters, path length z_p and off-path viewing distance d_c , discussed in (d). (d) A canonical model of forward movement, where the observer always fixates on the direction of motion. Forward movement requires “space ahead” to move into, and so the distances to objects in the direction of motion will tend to be greater than the distances in other directions (thus the triangular “path” ahead shown). In the figure, the observer is the black dot, seen from above, who has just arrived via a “path” below, has turned approximately 45 degrees left, and has found the beginnings of a new “path”, or space, to move forward into, namely directly north. This new “path” is of length z_p (and starting width w_p). Walking on a roadway would mean a large z_p . Outside the path, the gray region, is presumed to have a uniform probability density of objects. Objects, unless transparent, occlude one’s view (see Changizi et al., under review, for the connection between occluding clutter and the evolution of forward-facing eyes), and the ability to see exponentially decays as a function of distance. The average distance seeable into the off-path region is some constant, d_c . The solid contour in the off-path region delineates the average viewable distances from the observer. We can use this contour to make canonical predictions about how stimulus properties vary as a function of angle from the direction of motion. The six plots in (c) each have four curves, one for each of the following settings of the parameters z_p (the path length) and d_c (the off-path viewing distance): (i) $\langle z_p, d_c \rangle = \langle 5, 2 \rangle$, (ii) $\langle 20, 2 \rangle$, (iii) $\langle 5, 8 \rangle$, (iv) $\langle 20, 8 \rangle$. The path width, w_p , is set to 1.

2.4. Optic Flow Regularity Type I: Correlates of Direction of Motion

We first describe the correlates of the observer's direction of motion. Figures 2a and 2b are photographs taken while in forward motion, and the observer's direction of motion is obvious, for there are many cues for it. Many of the correlates of the direction of motion can be understood by examination of Fig. 2, and we enumerate them below.

A region of the visual field nearer to the observer's direction of motion tends to have

- (1) *Smaller projected sizes.*
- (2) *Smaller projected speeds.*
- (3) *Greater luminance contrasts.*
- (4) *Greater distances from the observer.*
- (5) *Lower eccentricity.*
- (6) *Lower projected distance from the vanishing point of converging lines.*

These six correlates are recorded in Fig. 2c. Notice that correlate (6) is just the correlate mentioned earlier concerning the classical geometrical illusions.

Although Fig. 2 provides example forward-moving scenes, the most fundamental reason for these correlates is this: *When one moves forward, one must avoid obstacles lest one collide with them.* When moving forward, the direction of motion is therefore different than other places in the visual field, for the direction of motion must have some "room for forward movement". That is, the distance must be sufficiently great for some degree of forward movement. The other places in the visual field, however, are not under any such constraint: they can be near or far. That is, regions of the visual field nearer to the direction of motion will correlate with being farther from the observer. This argument is very general, and would even apply, say, for a rocket ship moving within an asteroid field, where there is no ground plane. In the real world that we inhabit, there is a ground plane, and very often walls and ceiling, and in these circumstances the correlation between direction of motion and distance from the observer is even stronger. For the reasons just mentioned, correlate (4) follows. What about the other five correlates? We already discussed correlate (6) in the Subsection 2.2 when we reviewed the perceiving-the-present explanation of the classical geometrical illusions. Correlate (1) follows from correlate (4) because as an object nears the observer, its projected size increases (i.e., nearer objects have greater

projected size). Because distance and projected size are independent of an observer's pattern of fixation, correlates (1) and (4) are true no matter the manner in which a moving observer retinally tracks. The other correlates depend on the observer's pattern of fixation, however. We now consider the two possible cases.

Case 1, a constant angle of fixation relative to the direction of motion: If an observer's fixation is at some constant angle relative to the direction of motion—i.e., the observer does not fixate on approaching objects—then correlates (2), (3) and (6) result for the following reasons. Correlate (2) follows from correlate (4) because as an object nears the observer, it will also tend to be a greater projected distance from the direction of motion, and its projected speed will increase. Correlate (3) follows, in turn, because luminance contrast and projected speed are inversely related. To see why, consider an object flowing across a one-degree-long segment of the projection sphere. The luminance contrast at that one-degree-long segment is just (roughly) the magnitude of the difference in luminance between it and that of the background luminance. Objects with greater projected speed integrate along the one-degree-long arc for a shorter period of time, and thus the luminance of that arc—being so "smeared"—will differ less from that of the surround (or background) luminance. See the Subsection 2.2 for discussion of correlate (6). Correlate (5), though, may not hold if one is fixated at a large angle from the direction of motion. However, if one makes the eminently reasonable assumption that forward-moving observers have a tendency to look roughly in the direction they are going—something argued to be optimal (Wann and Swapp, 2000) and for which there is evidence that people do (Wilkie and Wann, 2003)—correlate (5) does follow. So, if observers tend to fixate at some constant angle relative to the direction of motion, and if they tend to look roughly where they are going, then all the correlates follow.

Case 2, fixating on approaching objects: However, observers often fixate on approaching objects, rather than fixating at some constant angle relative to the direction of motion. When fixated on an approaching object, the focus of expansion of outflowing dots will be at the point of fixation, not the direction of motion (Regan and Beverly, 1982). The fixated point, and not the direction of motion, will then tend to have smaller projected speeds,

greater luminance contrasts, lower eccentricity, and lower projected distance from the vanishing point of converging lines. That is, correlates (2), (3), (5) and (6) will not necessarily hold. However, as mentioned above, forward-moving observers tend to look where they are going—that is, lower eccentricity tends to correlate with heading—and the focus of expansion consequently tends to covary with the direction of motion, and (2), (3), (5) and (6) therefore *do* follow (and (1) and (4) were independent of fixation patterns).

In summary, we have just derived that correlates (1) through (6) are true for forward-moving observers no matter their fixation patterns (i.e., no matter whether Case 1 or 2), so long as they tend to look approximately where they are going. Although these conclusions are qualitative, and therefore do not enable us to make quantitative predictions of the probability distribution of the observer's direction of motion given a stimulus, they are rigorous, highly general and suffice for the qualitative predictions we will make concerning the direction of misperceptions (as opposed to the magnitudes of the misperceptions).

For the purpose of a more quantitative treatment of these six correlates, we also created a simple model of a forward-moving observer where we explicitly incorporate the key property of forward-moving observers, that the distances to objects in the direction of motion tends to be greater than in other directions because a requirement of forward movement is that there be space ahead to move into. The observer is also assumed to always fixate on the direction of motion. Fig. 2d depicts an aerial view of an observer (the dot) who is moving north (having just turned north from a northeasterly direction of movement) through an environment with objects strewn about. The gray region indicates regions of uniform probability density that there is an object, and the white areas indicate the regions chosen by the observer for forward-motion into (i.e., the “paths” through the environment found by the observer). The model assumes that the observer can see, on average, objects at some fixed distance inside the off-path region (because object occlusions will create some typical length scale of viewability for any given kind of environment). The solid contour in the gray region shows the average object positions visible to the observer (each at a fixed radial distance beyond the path from the observer), and on the basis of this one can derive the canonical distance to an object as a

function of the projected angular distance from the direction of motion (Fig. 2c, plot for correlate 4). Angular sizes of objects at these distances can be derived, thereby allowing one to plot typical projected sizes of objects as a function of projected distance from the direction of motion (Fig. 2c, plot for correlate 1). Angular velocities of objects at those positions in the environment can also be computed (Fig. 2c, plot for correlate 2), and the luminance contrast as proportional to the inverse of the angular velocity (Fig. 2c, plot for correlate 3). Eccentricities of the observer follow directly from the assumption of the model that the observer fixates on the direction of motion (Fig. 2c, plot for correlate 5). The probability that an object is moving sufficiently fast to “create” a converging optic-blur line on the retina is presumed to be proportional to the average angular velocity (Fig. 2c, plot for correlate 6). One can see from the plots in Fig. 2c that, for a wide variety of settings of the path length and the off-path viewing distance, the relationships conform to the correlates we derived more generally above.

Several observations are important to mention. (i) One must recognize that even though “projected sizes tend to be smaller near the direction of motion,” it does not follow that every stimulus with a projected size gradient is a stimulus that would be naturally encountered while the observer is in motion. That is, these ecological regularities tell us that ecologically natural optic flow stimuli have certain characteristics (like a projected size gradient), but they do not tell us that any stimulus with these characteristics is ecologically natural. A similar point of caution holds for correlates (2), (3) and (4) as well. For example, although ecologically natural optic flow stimuli have lower projected speeds near the direction of motion, consider a stimulus with lower projected speed objects in one part of the stimulus, but where the objects have random directions. Such a stimulus may not be ecologically associated with optic flow. (ii) Note that these ecological regularities do *not* require an assumption of carpentered environments (and recall that converging lines may typically be due to optic smear). (iii) Note that correlate (3) implies that,

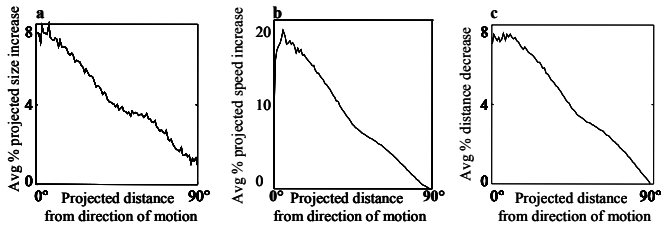


Figure 3

(a) The average percent projected size growth as a function of projected distance from the direction of motion. It was obtained by simulating 10^6 forward movements at 1 meter per second for 100 msec, and computing the average percent projected size growth of a line segment of random length (between a few cm and a meter), orientation, and placement (no more than 2 meters to the side, above, below, or in front of the observer's eye). We have confined objects to be relatively near the observer, since we believe that it is the dynamics of nearby objects that will have tended to shape the functions computed by the visual system. The qualitative shape of the plots does not change if the boundaries of the simulated world are scaled up uniformly. (b) and (c) are similar to (a), but recording, respectively, the average percent projected speed increase and the average percent distance decrease, each as a function of projected distance from the direction of motion. In sum, for relatively-nearby objects, projected size, projected speed, luminance contrast, and distance undergo greater percent change when nearer to the direction of motion.

when an observer is in motion, nearer objects tend to be lower in luminance contrast, which is in contradistinction to the weaker ecological regularity governing when an observer is not moving, where nearer objects tend to have greater luminance contrast.

2.5. Optic Flow Regularity Type II: How Quickly Features Change Depending on Nearness to the Direction of Motion

With the six ecological correlates of direction of motion now enumerated, we must discuss another kind of ecological regularity, one concerning the *rates* at which change occurs as a function of projected distance from the direction of motion. (By “projected distance from the direction of motion” we mean the visual angle between the observer direction of motion and some object in the visual field.) When an object is near to passing you, and the projected distance from the direction of motion is accordingly great, its projected size and speed have nearly asymptoted to their maxima, its luminance contrast has nearly reached its minimum (since it varies inversely with speed), and its distance from the observer has reached its minimum. Said differently, projected size, projected speed, luminance contrast, and distance (from the observer) undergo little change when close to 90 degrees from the observer's direction of motion;

these features undergo their significant changes when nearer to the direction of motion.

It is possible to derive the following ecological regularities concerning the rates of growth:

For two objects of similar distance from passing the observer, the one nearer to the observer's direction of motion undergoes, in the next moment,

- (A) a greater percent increase in projected size,
- (B) a greater percent increase in projected speed,
- (C) a greater percent decrease in luminance contrast, and
- (D) a greater percent decrease in distance from the observer.

These intuitions can be made rigorous by simulating forward movement. Fig. 3a shows how the growth of projected size varies as a function of projected distance from the direction of motion: projected sizes tend to increase most when very near the direction of motion, to increase by about half that when at 45° from the direction of motion, and to not increase at all when passing the observer. Similar conclusions hold for projected speed (and thus luminance contrast) and distance, as Figures 3b and 3c show. In our simulations we assume that the objects are “relatively nearby”, and specifically no more than 2 meters to the side, above, below, or in front of the observer's eye. This “relatively-nearby” assumption is reasonable for two reasons. First, the objects where latency-compensation is most needed are the ones near enough to interact with; there will be little or no selection pressure for the compensation of objects, say, 100 meters distant from an observer (Cutting and Vishton, 1995). Second, most objects very far away will simply be too small to notice, and, furthermore, any changes they undergo will be small in absolute magnitude, and thus insignificant compared to the changes of nearby objects. (Note that this “relatively-nearby” was not made for Optic Flow Regularity I concerning the six correlates of the observer's direction of motion, because even far-away, unchanging stimulus features—despite not requiring compensation—can provide information concerning the observer's direction of motion.) However, the qualitative shapes of the plots in Fig. 3—and correlates (A) through (D)—are general; for example, increasing the 2 meter limit to some larger value does not modify the shape of the plots. The

main qualitative result is due to the simple fact that, as mentioned above, objects near to passing you are no longer undergoing percent change in projected size, projected speed, luminance contrast, and distance.

2.6. Twenty Eight Distinct Ecological Regularities

We have now introduced the two broad kinds of ecological optic flow regularity: (I) correlates-of-direction-of-motion, and (II) how-quickly-features-change-nearer-the-direction-of-motion. Within the first kind we introduced six correlates of the direction of motion [(1) through (6) from above], and within the second kind we introduced four features that change more quickly in the next moment when nearer to the direction of motion [(A) through (D) from above]. These two kinds of optic flow regularity are robust, qualitative, statistical generalizations, and do not rely upon any post-hoc setting of parameters. It is important to understand that, although these two kinds of regularity are related, they are very different, and are independent of one another. Given a stimulus, the first group of regularities [(1) through (6)] helps us to determine, from the stimulus, the observer's direction of motion. These six play the same role as the converging lines did in the classical geometrical illusions: we argued in Subsection 2.2 that the vanishing point of converging lines is probably the observer's direction of motion. This converging-line regularity is now just one of six such regularities. Once we have used the first group of regularities to determine the observer's direction of motion—e.g., the observer is moving toward the vanishing point of the converging lines—we then need to determine how features will change in the next moment were the observer to move in that direction. The second group of regularities [(A) through (D)] tells us how features change in the next moment; the rate at which features change depends on where they are in the visual field relative to the observer's direction of motion. On average, nearby objects that are closer in the visual field to the observer's direction of motion will undergo greater change in the next moment (i.e., the derivative is steep nearer the direction of motion). And this is what the second group of regularities told us. For example, for the Orbison illusion as shown in Fig. 1, given that the observer is moving toward the vanishing point (something determined via the first group of regularities), we want to know how the projected nature of the square will change in the next

moment. This latter issue is answered via knowing that the projected sizes of objects tend to increase more in the next moment when they are nearer to the observer's direction of motion, and so the left side of the square in the Orbison illusion will grow more in the next moment than the right side. (And importantly, the left and right side of the square are probably not too different in distance from passing the observer; namely, in this case they probably lie in the observer's fronto-parallel plane, and so are equally distant from passing the observer.)

Together, these two kinds of ecological regularity tell us which parts of the visual field will undergo greater feature changes in the next moment. In particular, from the six correlates-of-direction-of-motion regularities and the four how-quickly-features-change-nearer-to-the-direction-of-motion regularities, one can distinguish between $6 \times 4 = 24$ distinct ecological regularities. Consider, for example, combining together (1) and (B) (we shall call such a combination "1B"). This combination determines a specific ecological regularity, namely (1) that a region of the visual field with lower projected sizes tends to be nearer the direction of motion, and (B) for two objects of similar distance from passing the observer, the one nearer the direction of motion tends to undergo, in the next moment, a greater percent increase in projected speed. From this we may reasonably infer the following more succinct statement of 1B: *for two objects of similar distance from passing the observer, the one nearer the region of the visual field with smaller projected sizes tends to undergo, in the next moment, a greater percent increase in projected speed.* Consider, as another example, combining (3) and (C) to make ecological regularity 3C: (3) a region of the visual field with greater luminance contrasts tends to be nearer the direction of motion, and (C) for two objects of similar distance from passing the observer, the one nearer the direction of motion tends to undergo, in the next moment, a greater percent decrease in luminance contrast. Again, it is reasonable to expect that the following shorter statement of 3C is true: *for two objects of similar distance from passing the observer, the one nearer the region of the visual field with greater luminance contrasts tends to undergo, in the next moment, a greater percent decrease in luminance contrast.*

Table 1

Prediction of the optic flow regularities hypothesis. Catalog of the 28 ecological correlates of forward motion, and the 28 illusion classes from the perceiving-the-present framework due to the effects of seven direction-of-motion correlates (the rows) on perceived projected size, projected speed, luminance contrast, and distance (the columns). To illustrate how to read the table, the following is how the upper left case of the table, illusion class 1A, should be read: “A region of the visual field with lower projected sizes (greater projected spatial frequency) is associated with, in the next moment, (i.e., the predicted perception is of) a greater increase in projected size (greater decrease in projected spatial frequency).” Each square also shows an example figure consisting of (a) two targets that are identical in the modality of the column, but (b) differ with respect to the feature of the row. The probable direction of observer motion is always toward a point on the left side. For Row (2) and Column (B)—each which concern motion—arrows are used to indicate stimulus speed and direction. For Row (4) stereograms are used for the example figures; although we have used stereo disparity to cue relative distance, any cue to relative distance could be used. For Row (5) the little eye in the figures represents the approximate fixation point.

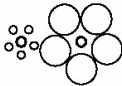
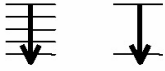

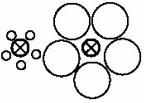

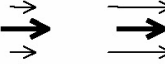




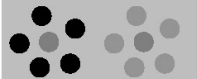


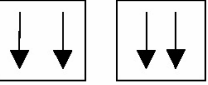
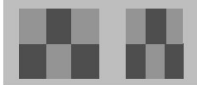
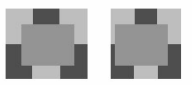

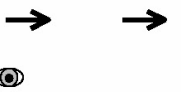

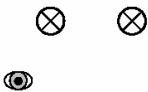
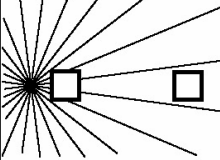
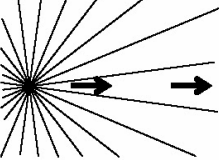
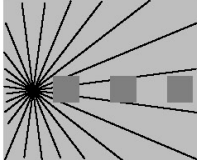
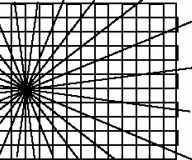
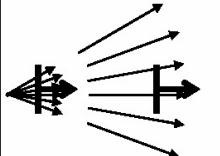
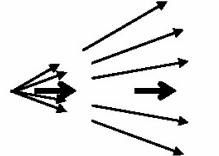
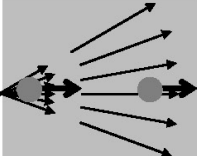
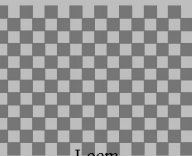
For two objects of similar distance from passing the observer, the one nearer the region of the visual field with... ↓	...tends to undergo, in the next moment (i.e., the predicted perception is of)...			
	(A) ... a greater increase in (angular) size (i.e., larger on left)	(B) ... a greater increase in (angular) speed (i.e., faster on left)	(C) ... a greater decrease in luminance contrast (i.e., lower contrast on left)	(D) ... a greater decrease in distance (i.e., nearer on left)
(1) ... lower (angular) sizes...				
(2) ... lower (angular) speeds...				
(3) ... greater luminance contrasts...				
(4) ... greater distances...				
(5) ... lower eccentricity...				
(6) ... lower (projected) distance from vanishing point...				
(7) ... lower (projected) distance from focus of expansion...				

Table 1 is a matrix showing all 24 of these ecological regularities, with the correlates of the direction of motion as the rows, and, as the columns, the four features that change more quickly when nearer to the direction of motion. The table also includes a seventh row, where the correlate of the direction of motion is the focus of expansion of optic flow itself (such stimuli tend to possess more than one of the six stated correlates of the direction of motion). In total, then, Table 1 catalogs 28 distinct ecological regularities relating disparate stimulus types to four modalities of perception.

2.7. Twenty Eight Distinct Predicted Illusion Classes

What do these ecological regularities have to do with visual perception? These 28 distinct ecological regularities are important because they *also* amount to 28 distinct predicted illusion classes. This is because, under perceiving-the-present, the perception is predicted to be representative of the way the scene will be in the next moment (i.e., by the time the perception occurs). Each ecological regularity in Table 1 states how features will change in the next moment, and perceiving-the-present therefore expects observers to have perceptions that accord with these expected next-moment features. More specifically, the predicted illusions recorded in Table 1 can be described as follows: For each class there are two similarly distant target objects that are identical in regards to the column-modality. The region of the visual field near the left target is given the features specified by the row, and this thereby makes it probable that the left region is nearer to the observer's direction of motion. The target object on the left is therefore predicted to be perceived by observers to have a column-modality that changes in the way stated in the column heading.

For example, ecological regularity 1A states that *for two objects of similar distance from passing the observer, the one nearer the region of the visual field with smaller projected sizes tends to undergo, in the next moment, a greater percent increase in projected size*. Perceiving-the-present accordingly predicts that, when an observer is presented with a stimulus with two targets of similar distance from the observer, one in a region with small projected size features and another in a region with large projected size features, the observer should overestimate the

projected size of the target within the small-projected-size region. As an example stimulus, consider the one in the spot for 1A in Table 1 (this figure is the Ebbinghaus, or Titchener, illusion). The left side of the figure has, overall, smaller projected size features than the right side of the figure, and thus the left target, being probably nearer to the direction of motion, should undergo, in the next moment, a greater percent increase in projected size. Since the two targets (i.e., the center circle on the left and the center circle on the right) have identical projected sizes, the left target will undergo, in the next moment, a greater increase in projected size than the one on the right, and perceiving-the-present expects observers to perceive the left target to project larger than the one on the right. Intuitively, the probable scene in 1A is of two identical circles on the left and right, at similar distance from the observer (see discussion below); but where the one on the left, being surrounded by smaller projected size features, is probably nearer to the observer's direction of motion, and will undergo greater percent growth in the next moment. Consider as another example ecological regularity 1B, and the figure shown for it in Table 1. Here, the target objects are objects moving at identical projected speed (indicated in the figure by arrows of identical length) over the horizontal lines, since (B) is the column for perceived projected speed. The horizontal lines on the left side of the stimulus have smaller projected size features (or greater projected spatial frequency), thus making that part of the stimulus probably nearer to the direction of motion (as indicated by (1)). We therefore expect that the left target will undergo a greater percent increase in projected speed in the next moment, as the column heading states. Perceiving-the-present accordingly predicts that observers should perceive the projected speed of the target on the left to be greater than that of the same-speed target on the right (since that is how they would typically be in the next moment).

2.8. Arguments that the targets in illusions are treated as similarly distant from the observer

We will see in Section 3 that the illusions tend to be consistent with perceiving-the-present's predicted table of illusions in Table 1. However, unlike traditional explanations for illusions which rely upon claims about one target probably being farther away, our treatment supposes that the target objects tend to be treated by the visual system as if they are

similarly distant. There are several reasons for believing that target objects in illusions and figures like those in Table 1 are treated by the visual system as similarly distant.

One reason is that the illusions do not change when strong cues are added that the targets are similarly distant. For example, in the Ponzo illusion in Fig. 1 the stimulus is ambiguous as to the distances of the two bars, and one possibility is that the stimulus is due to a scene where the top horizontal bar is farther from the observer (and another possibility is that the two targets are at similar distance from the observer). However, consider now the Orbison illusion in Fig. 1, where the two horizontal bars are now part of a square stimulus. It is highly probable that the square stimulus is due to a real-world square in the observer's fronto-parallel plane, as opposed to a real-world trapezoid tilted backward in just the right manner so as to coincidentally project as a perfect square. In the Orbison illusion, then, the cues suggest that the upper and lower bars are probably at about the same distance from the observer (and this applies even more strongly for the grid illusion in Fig. 1), and yet, importantly, the Ponzo-like illusion still is present.

The second reason for believing that target objects in illusions are treated by the visual system as similarly distant from the observer is that many illusions possess cues suggesting that the targets are, indeed, at similar distances from the observer. For example, in most illusions the two target stimuli are identical to one another (in projected size, shape, pattern, speed, and luminance), and the differences causing the illusion are in the surrounding stimuli, not in the targets themselves. [This is true for most of the example stimuli in Table 1, namely 1A, 1B, 1D, 2A, 2B, 2C, 3A, 3B, 3C, 5A, 5B, 5C, 5D, 6A, 6B, 6C, 7A, 7B, 7C (where it is assumed that the vectors represent moving objects that are identical in projected size, shape, pattern and luminance).] This is, in fact, one of the central characteristics of a good illusion: that despite two stimuli being identical, they are perceived differently. But when two stimuli are identical, it significantly raises the probability that the targets are the same kind of object—it would be a rare coincidence that two different kinds of object in a scene would cause a stimulus with identical stimulus properties. It follows that if two objects are the same kind of object (having identical distal size), then because they project the same size in the stimulus, the

two targets must probably be at the same distance from the observer. Thus, one of the central characteristics of a good illusion—having identical target stimuli—is itself a cue that the targets are at similar distance. Another kind of cue that two targets are at similar distance from the observer occurs in some illusions (e.g., in 2D, 3D, 4D, 6D and 7D of Table 1), namely when the targets are the opposite ends of a single rectangularly projecting plane or grid (of uniform luminance). As mentioned in the previous paragraph, a rectangular stimulus is probably due to a real-world rectangle in the observer's fronto-parallel plane—not due to a real-world trapezoid tilted in just such a manner as to coincidentally project rectangularly. Therefore, the opposite ends of the rectangular plane are at similar distances from the observer. Finally, illusions can have an even stronger cue that they are at similar distances from the observer, namely when identical binocular disparity is used (as in Row 4 of Table 1).

A third reason for believing that the visual system might treat the targets in illusions as similarly distant from an observer is that, even if in a given stimulus the cues are weak that the targets are similarly distant, there are benefits for assuming, for perceiving-the-present compensation purposes, that the targets are at similar distances. For specificity, consider the Ponzo illusion (Fig. 1), and consider two possible interpretations of the stimulus: (a) the lower bar is close to the observer but the upper horizontal bar is far, and (b) both bars are similarly close to the observer. Although in the previous paragraph we provided reason to believe that even here the bars are probably at similar distance from the observer (because the two bar stimuli are identical), let us suppose now for the sake of example that these two possible interpretations are equally probable. If the observer perceives according to (a) but in fact (b) is the case, then the costs are potentially high because the upper bar will not be perceived veridically, and the observer is in danger of not interacting appropriately with the bars (e.g., collision). If, on the other hand, the observer perceives (b) but (a) is the case, then the costs are low because, although the observer will not perceive the upper bar veridically (the upper bar's perceived angular size will be larger than the lower bar), the observer is far from the upper bar and not at risk of an inappropriate interaction with it (such as a collision).

2.9. Summary of perceiving-the-present prediction

In sum, Table 1 possesses two distinct but related kinds of content: (a) ecological regularities concerning how features tend to change in the next moment depending on their current features, and (b) predicted perceptions based on the perceiving-the-present hypothesis. Table 1 essentially predicts that there should be an underlying *pattern* to the kinds of illusions researchers have found, a pattern cutting across a broad spectrum of the visual perception literature. This predicted pattern is fixed once we determined the ecological correlates. Rather than attempting to experimentally test each of these 28 classes of illusion ourselves, for the purposes of this paper we have opted to test these predictions via conducting a broad survey of the visual perception literature, which is the subject of the second half of this paper. We will see that the predicted pattern appears to exist.

Before moving to the next section, it is important to understand the kind of prediction we are making. Although for any predicted illusion class, illusions within that class may be empirically known, it is *not* empirically known what the *pattern* is across the 28 distinct stimulus types. Our prediction concerns this underlying pattern: it should fit the regularities shown in Table 1. Note that this is significantly different from pooling together known cases of phenomena that appear to be consistent with one's hypothesis. As an analogy to the kind of prediction we are making, one of us (MAC) has a theory for how the number of neocortical areas should increase as a function of brain size (namely, a cube root law). Given the prediction of the theory, MAC sought to test it via determining how the number of areas actually *does* increase as a function of brain size. To do this, he used the published literature to compile area counts and brain size measures, and was thereby able to find support for the prediction. But, one might complain, all the neocortical area and size information used in the plot were already known in the literature, and so no new prediction had been made by the theory. If we take such a complaint seriously, MAC would have to acquire area counts from new species before it could be called a prediction. The mistake in such a criticism is that, although each datum may have been known, the pattern made by compiling all the data had *not* been known. Similarly, the pattern across the 28 distinct stimulus types was not known prior to our

investigation; what the pattern is, then, is an open empirical question, and our theory predicts what the pattern's "shape" is. The following section empirically investigates this pattern.

Also, we must admit the limits of this predicted pattern: we cannot predict that *every* stimulus fitting within the stimulus type of one of the classes will have the predicted kind of illusion. The main reason for this is that the ecological regularities we presented earlier are statistical *tendencies*, not inviolate laws; they will sometimes fail, and some kinds of stimuli may be associated with those failure cases. This is again analogous to the neocortex-area example discussed above, where a predicted cube-root law relating number of areas to brain size does *not* mean that we do not expect outliers in some cases; of course we expect outliers, but we nevertheless expect the pattern to exist. As a cartoon example to make our point, imagine that observers typically steer away from spiders, and typically steer toward lakes for the purpose of drinking. A stimulus with small projected size features on the left, but with spider shapes, and a large projected size on the right, with cues it is a lake, may in fact be ecologically associated with movement toward the lake, the larger projected size features; this would be counter to the ecological regularity in 1A of Table 1. We cannot possibly discount such possibilities. Our theory should be treated as a zeroth-order hypothesis. Nevertheless, our claim is that the *central* trend for any stimulus type will be as predicted by the general pattern. And, as we will see in Section 3, there are indeed central trends in the literature for the kinds of illusions found of a given stimulus type: they are often the kinds of illusions the community has names for, because they are so strong, or because they are so robust.

3. The empirical generalization concerning 28 illusion classes

Here in the second half of the paper we put forth evidence that there is a broad, as yet unnoticed, empirical regularity or pattern across a large swathe of visual illusions—that more than 50 kinds of illusion may be systematically organized into a 7 by 4 table of 28 illusion classes. Our finding of the empirical regularity we describe here was motivated by the prediction of the perceiving-the-present, optic-flow-regularities hypothesis we presented in the first

half of the paper. However, we recognize that any theory of an empirical regularity is necessarily more contentious than the empirical regularity itself, and we wish to emphasize the importance of the empirical regularity, even if one is not yet willing to believe that perceiving-the-present is an adequate explanation of it.

Table 2 is like the “prediction table” Table 1, but it is the “illusion evidence table,” where within each of its matrix boxes we have recorded illusions from the literature that fall within the corresponding stimulus class, along with citations. (A *stimulus class* consists of illusions where stimulus modality X affects perceived modality Y.) Any given stimulus from the literature falls within a well-defined stimulus class, and illusions were placed in the appropriate stimulus class of the table whether or not the illusion was as predicted by the hypothesis. Where an illusion fits in the table is usually unambiguous, and is based on the implicit judgement of the researchers studying the illusion. A researcher who has, for example, found that people perceive an object to project larger when stereo disparity indicates it is farther away has, him or herself, implicitly concluded that stereo depth information modulates the perception of projected (or angular) size. I.e., that distance information (row 4) modulates the perception of angular size (column A), and thus the studied illusion falls in box 4A.

For the remainder of this section we discuss Table 2 in detail. First we consider general aspects of the columns, and then, going row by row, we take up each of the 28 cases in the matrix. Citations are largely reserved for Table 2.

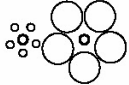
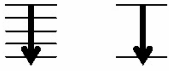

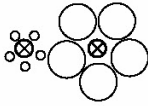

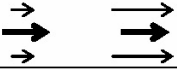







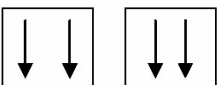
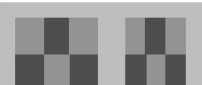

3.1. Column (A): Illusions of angular (or projected) size

Column (A) concerns illusions of perceived projected size, or cases where one object appears to have greater projected size than another, even though their projected sizes are identical. (This is not to be confused with row (1), which concerns illusions that are *due* to projected size differences in the visual field.) This column also includes misperceptions of projected distances across the visual field and misperceptions of projected angles (such as in the angles of the Orbison illusion).




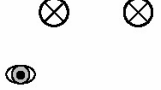
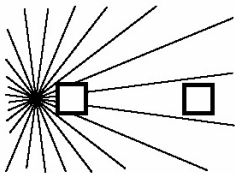
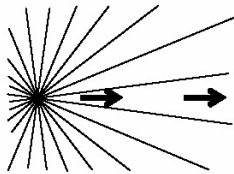
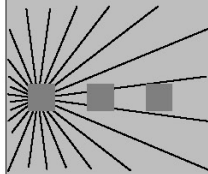
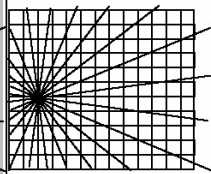
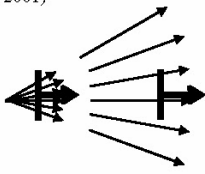
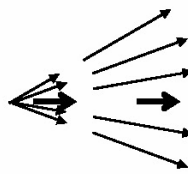
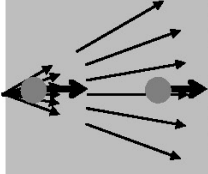
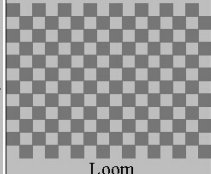
There is, in addition, another kind of misperception that falls within this column: “repulsion”. To understand this, consider a vertical line segment placed on the right side of a radial

display, crossing the horizontal meridian. Its perceived projected size is overestimated, and the overestimation is greater the nearer it is to the vertical meridian (see our earlier discussion of the classical geometrical illusions, and Fig. 1). But the effect can simultaneously be considered a misperception of the perceived projected positions of the top and bottom endpoints of the line segment: each endpoint is perceptually repulsed away from the center of the radial display, and since each has a vertical component to the repulsion, the projected distance between the endpoints increases. Because of this connection between perceived projected size and perceived projected position (relative to the location of the direction of motion), in this column we record illusions of perceived projected position as well as illusions of perceived projected size. For example, in class 5A (eccentricity affects perceived angular size) is “foveal repulsion”—the phenomenon that stimuli nearer to the fovea are perceived to be more peripheral than they are—which is essentially equivalent to the fact that less eccentric objects are perceived as projecting larger size. (See discussion of this versus foveal attraction under “Row 5” discussion below.) Also, in class 3A (luminance contrast affects perceived angular size) there is greater repulsion from higher contrast stimuli, in class 6A (vanishing point affects perceived angular size) there exists repulsion within radial displays (see the two-dot stimuli and psychophysical experiment in Changizi & Widders, 2002), and in class 7A (focus of expansion affects perceived angular size) is “flow repulsion” (found in conditions of motion capture).

Table 2.
7 by 4 table of 28 illusions classes catalogued from the visual perception literature. This table serves as data with which to test the prediction of Table 1.

	(A) ...perceived (angular) <i>size</i>	(B) ...perceived (angular) <i>speed</i>	(C) ...perceived <i>luminance contrast</i>	(D) ...perceived <i>distance</i>
(1) How (angular) <i>size</i> affects...	<p>—size contrast (MacKay, 1973; Klein et al., 1974; Georgeson, 1980) —Ebbinghaus/Titchener illusion (Massaro & Anderson, 1971; Coren & Girgus, 1978; Weintraub & Schneek, 1986) —moon illusion (Kaufman & Rock, 1962; Rock & Kaufman, 1962; Restle, 1970; McCready, 1986; Plug & Ross, 1994; Kaufman & Kaufman, 2000; Redding, 2002) —nearer horizon \Rightarrow larger (Gilinsky, 1955; Leibowitz & Harvey, 1969) —Oppel-Kundt/Botti illusion (Oppel, 1854; Lewis, 1912; Rentschler et al., 1981; although counter at high spatial frequency, Rentschler et al., 1981)</p> 	<p>—smaller background features \Rightarrow faster (Brown, 1931; Johansson, 1950; Gogel & McNulty, 1983) —greater dot density of moving object \Rightarrow faster (Watamaniuk et al., 1993) —greater spatial frequency \Rightarrow faster (Diener et al., 1976; McKee et al., 1986; although counter at high spatial frequency, Smith & Edgar, 1990) —smaller patterns \Rightarrow faster (Snowden, 1999) —greater spatial frequency \Rightarrow less capture \Rightarrow greater relative speed (De Valois & De Valois, 1991)</p> 	<p>—greater spatial frequency \Rightarrow greater "assimilation" (Helson, 1963; Steger, 1969; Walker, 1978) —greater spatial frequency surround \Rightarrow lower contrast (McCourt, 1982; Yu et al., 2001)</p> 	<p>—smaller surround \Rightarrow nearer (Ebbinghaus/Titchener, McCready, 1985) —horizon moon appears nearer (Epstein et al., 1961; Boring, 1943, 1962; Rock & Kaufman, 1962; McCready, 1986)</p> 
(2) How (angular) <i>speed</i> affect...	<p>—slower \Rightarrow larger (Ansbacher, 1944; Virsu et al., 1974; Parker, 1981, 1983; Kaneko & Uchikawa, 1993) —longer presentation time \Rightarrow slower (Katz et al., 1990; Treue et al., 1993) \Rightarrow lower spatial frequency (Tynan & Sekuler, 1974; Virsu et al., 1974; Virsu & Nyman, 1974; Kulikowski, 1975; Gelb & Wilson, 1983; Maddess & Kulikowski, 1999)</p> 	<p>—motion contrast (Loomis & Nakayama, 1973; Walker & Powell, 1974; Tynan & Sekuler, 1975)</p> 	<p>—lower speed surround \Rightarrow lower contrast (Takeuchi & de Valois, 2000) —longer presentation time \Rightarrow slower (Katz et al., 1990; Treue et al., 1993) \Rightarrow lower contrast (Kulikowski, 1972)</p> 	<p>—lower speed surround \Rightarrow nearer (motion parallax-induced depth contrast, Graham & Rogers, 1982; Rogers & Graham, 1983)</p> 
(3) How <i>luminance contrast</i> affects...	<p>—greater contrast \Rightarrow stronger geometrical illusions (Wallace, 1975; Dworkin, 1997) —color equiluminance \Rightarrow absence of geometrical illusions (Livingstone & Hubel, 1987) —greater contrast \Rightarrow larger (Robinson, 1954; Weale, 1975; Georgeson, 1980; de Weert et al., 1998) —greater contrast \Rightarrow lower spatial frequency (Virsu, 1974; Virsu & Vuorinen, 1975; Kulikowski, 1975; Georgeson, 1980; Gelb & Wilson, 1983; Maddess & Kulikowski, 1999) —greater contrast \Rightarrow greater repulsion (Rentschler et al., 1975)</p> 	<p>—greater contrast \Rightarrow faster (Hess, 1904; Thompson, 1982; Stone & Thompson, 1992; Kooi et al., 1992; Müller & Greenlee, 1994; Hawken et al., 1994; Ledgeway & Smith, 1995; Gegenfurtner & Hawken, 1996; Snowden et al., 1998; Blakemore & Snowden, 1999; Brooks, 2001) —greater contrast moving surround \Rightarrow greater induced target speed (Raymond & Darcangelo, 1990) —greater contrast \Rightarrow less capture \Rightarrow greater relative speed (Ramachandran, 1987; Ramachandran & Anstis, 1990; Murakami & Shimojo, 1993; Zhang et al., 1993)</p> 	<p>—luminance contrast contrast (Ejima & Takahashi, 1985; Chubb et al., 1989; Cannon & Fullenkamp, 1991, 1993; Solomon et al., 1993; Snowden & Hammett, 1998)</p> 	<p>—color equiluminance \Rightarrow absence of depth (Livingstone & Hubel, 1987) ? —greater contrast surround \Rightarrow nearer (BELOW)</p> 
(4) How greater <i>distance</i> affects...	<p>—greater stereo depth \Rightarrow larger (Enright, 1989; Kaneko & Uchikawa, 1997; de Weert et al., 1998) —lower accommodation \Rightarrow larger (Biersdorf et al., 1963) —lower convergence \Rightarrow larger (Thouless, 1931; Heinemann et al., 1959; Biersdorf et al., 1963; Oyama & Iwawaki, 1972; Komoda & Ono, 1974)</p> 	<p>—farther \Rightarrow faster (follows from 4A)</p> 	<p>—farther \Rightarrow lower contrast (?)</p> 	<p>—depth contrast (Werner, 1938; Harker, 1962; Pastore, 1964; Pastore & Terwilliger, 1966; Anstis et al., 1978; Brookes & Stevens, 1989; Pierce et al., 1998; van Ee et al., 1999; te Pas et al., 1997; Sato & Howard, 2001)</p> 

...Table 2 continued

	(A) ...perceived (angular) <i>size</i>	(B) ...perceived (angular) <i>speed</i>	(C) ...perceived <i>luminance contrast</i>	(D) ...perceived <i>distance</i>
(5) How lower eccentricity affects...	<p>—nearer fovea ⇒ larger (William James, 1890/1950; Helmholtz, 1867/1962; Newsome, 1972; Schneider et al., 1978; Georgeson, 1980; Davis, 1990)</p> <p>—Hering illusion without the radial display (Helmholtz, 1867/1962, see Liu & Schor, 1998).</p> <p>—foveal attraction or repulsion? (Mateeff & Gourevich, 1983; see Appendix for discussion)</p> 	<p>—nearer fovea ⇒ faster (Campbell & Maffei, 1981; Tynan & Sekuler, 1982; Pantle, 1992; Schlykova et al, 1993).</p> <p>—nearer fovea ⇒ greater stereomotion speed (Brooks & Mather, 2000)</p> <p>—nearer fovea ⇒ less capture ⇒ greater relative speed (De Valois & De Valois, 1991; Murakami & Shimojo, 1993; Zhang et al., 1993).</p> 	<p>—nearer fovea ⇒ lower contrast (Georgeson, 1991)</p> 	<p>—nearer fovea ⇒ nearer (barrel-distortion of large fronto-parallel planes, Helmholtz, 1867/1962)</p> 
(6) How the vanishing point affects...	<p>—classical radial-display illusions such as Ponzo, Hering, Orbison (Ehrenstein, 1925; Orbison, 1939; Berliner & Berliner, 1948; Leibowitz et al., 1969; Coren et al., 1976; Coren & Girgus, 1978; Schiffman & Thompson, 1978; Weale, 1978; Jordon & Randall, 1987; Changizi, 2001, 2003; Changizi & Widders, 2002)</p> 	<p>—nearer center of radial display ⇒ faster (Swanston, 1984; Cesàro & Agostini, 1998)</p> 	<p>—nearer center of radial display ⇒ lower contrast (BELOW)</p> 	<p>—nearer center of radial display ⇒ nearer (BELOW)</p> 
(7) How the focus of expansion affects...	<p>—nearer FOE ⇒ larger (Anstis, 1989; Ramachandran & Anstis, 1990; Whitaker et al., 1999; Experiments 2 and 3 of this paper)</p> <p>—flow repulsion, or capture (Ramachandran, 1987; Anstis, 1989; Ramachandran & Anstis, 1990; De Valois & De Valois, 1991; Murakami & Shimojo, 1993; Zhang et al., 1993; Whitney & Cavanagh, 2000)</p> <p>—forward induced motion ⇒ increased projected size (Farné, 1972, 1977; Reinhart-Rutland, 1983; Wade & Swanston, 1984; Whitaker et al., 1999)</p> <p>—looming toward grid causes center to bow out (Foster & Altschuler, 2001)</p> <p>—dynamic Zanker-Hering analog (Zanker et al., 2001)</p> 	<p>—nearer FOE ⇒ faster (follows from 2B)</p> <p>—looming illusions (Widders color-balls, Changizi, 2003)</p> <p>—looming toward grid causes center to flow out faster (Foster & Altschuler, 2001)</p> 	<p>—nearer FOE ⇒ lower contrast (?)</p> 	<p>—capture in depth (Anstis, 1989; Edwards & Badcock, 2003)</p> <p>—looming toward grid causes center to bulge (Foster & Altschuler, 2001)</p>  <p>Loom</p>

3.2. Column (B): Illusions of angular (or projected) speed

Column (B) includes illusions of perceived projected speed. Projected speed and projected size are similar in that projected size is the projected distance between two points in the visual field at one instant in time, whereas projected speed is the projected distance traveled during a unit time interval. We therefore expect that if a stimulus feature elicits a perception of increased projected size, then an object moving within this stimulus should be perceived to have an increased projected speed (since it will travel over a greater perceived projected distance per unit time). In a certain sense, then, columns (A) and (B) could be joined into a single column, but we have nevertheless kept them separate since (i) the corresponding illusion classes tend to be in distinct literatures, and (ii) despite the logic of the argument above for their equivalence, the visual system need not, in principle, follow this logic.

One phenomenon we find in this column concerns “motion capture” (Ramachandran, 1987), which is the phenomenon that a stationary target on a flowing background is perceived to have a velocity in the same direction as the background; the background “captures” the trajectory of the target. It follows that, when there is capture, the perceived *relative* speed (between target and background) is *reduced*; more capture means less perceived relative speed. We accordingly expect that features that lead to a *greater* increase in perceived projected speed (i.e., any of the row labels in Table 2) should also lead to *less* capture. Known cases of such motion capture modulation are recorded in classes 1B, 3B and 5B. (Motion capture is also found in class 7A because capture is known to shift the perceived projected position of targets in the direction of the optic flow (“flow repulsion”), and in class 7D because capture works in depth.)

3.3. Column (C): Illusions of luminance contrast

Column (C) incorporates illusions of perceived luminance contrast. Note that if an object’s luminance contrast with the surround (or background) is misperceived, then the luminance of the object or the surround, or both, must be misperceived. In particular, faster moving objects are lower in luminance contrast, which is to say their luminance becomes more like that of the surround. Thus, if a gray object on a white surround is perceived to have

lower luminance contrast, this is just to say that the gray object is perceived to have greater luminance (like that of the surround). For our pictures in this column, we have used uniform gray surrounds, with objects having lower luminance; since we expect the left target in each box to have lower luminance contrast, this is just to say that it should appear more luminant (or brighter) than the right target. (Accordingly, if the objects had greater luminance than the background, then we would expect the left target to appear less luminant.)

3.4. Column (D): Illusions of distance

Column (D) consists of illusions of perceived distance. As mentioned earlier, for every representative picture in the table, there are two targets that are identical with respect to the column modality for their class. This is crucial in making the stimuli “work” as illusions. For columns (A) through (C) the target stimuli must simply be made identical in projected size, speed, and luminance contrast, respectively. For column (D), however, the issue becomes more complicated because the distance of the targets cannot be unambiguously determined by the stimulus. Instead, for column (D), the two targets must be set so as to *probably* be at the same distance from the observer. See Section 2.8 for discussion of arguments that the target stimuli are treated as having similar distance from the observer.

3.5. Row (1): Illusions due to projected size

Row (1) possesses illusions that are due to one part of the visual field having smaller projected size features than the other, thereby making it probable that the direction of motion is in that part of the visual field. Note that it is known that projected-size-feature changes alone—without optic flow—can serve to cue forward motion (Schrater, Knill & Simoncelli, 2001).

Class 1A (projected size affects perceived projected size) consists of illusions of size contrast, where objects appear larger in projected size when surrounded by nearby smaller objects. This straightforwardly applies to cases like the Ebbinghaus (the figure shown) and the research cited under the heading “size contrast” in the table. Size contrast also probably underlies the moon illusion (where the horizon moon appears to have significantly greater projected size than the overhead moon despite their physical projections being identical), because the horizon moon is surrounded by nearby, small-

projected-size features, whereas the overhead moon is not. The research under the heading “nearer horizon \Rightarrow larger” is similar in this regard to the moon illusion, these studies showing that perceived projected size is increasingly overestimated as the target is moved farther away and thus nearer to the horizon. The Oppel-Kundt is shown as the figure in class 1B, but without the arrows, and the space divided by multiple lines appears to project larger than the undivided space; it is less well-known, however, that the Oppel-Kundt illusion eventually reverses for sufficiently many lines (Rentschler, Hilz, Sütterlin & Noguchi, 1981).

Class 1B (projected size affects perceived projected speed) consists of a number of subclasses. The first two subclasses are similar in that they deal with the size features of the background: either the projected sizes of the background features, or the dot density of the background features. The other three subclasses have to do with the projected sizes of the moving objects themselves. One of the more widely studied of these latter subclasses is the phenomenon that higher projected spatial frequency moving objects are perceived to move faster (i.e., have greater projected speed): the phenomenon holds for spatial frequencies in the ranges 0.01 to 0.1 c/deg (Diener, Wist, Dichgans & Brandt, 1976) and 0.5 to 1.5 c/deg (McKee, Silverman & Nakayama, 1986), but, as in the Oppel-Kundt, eventually reverses for sufficiently high spatial frequency, in the range of 2 to 4 c/deg (Smith & Edgar, 1990). See also Campbell and Maffei (1981) for a similar psychophysical function but for rotational motion. The figure shows an Oppel-Kundt (see class 1A) analog for this class, where there are two objects moving at identical projected velocity, one across the divided space, and the other across the undivided space.

For **class 1C** (projected size affects perceived luminance contrast), the central and long-known phenomenon is that thinner bars appear lower in contrast (“assimilation”), and the figure here is analogous to the Oppel-Kundt in some ways, except that the perception of interest now is luminance contrast, not projected size. However, at very low spatial frequencies ranges, such as about 0.25 to 1 cycle per degree, perceived contrast undergoes some minor increase as spatial frequency increases (after which perceived contrast decreases steadily with spatial frequency increase, see, e.g., Walker, 1978).

Finally, for **class 1D** (projected size affects perceived distance), it has long been observed that the horizon moon is not only perceived to project larger (1A), but is perceived to be nearer as well. (This is related to what is called the “size-distance paradox,” which is only a paradox when one equivocates between “projected size” and “distal size”, see Appendix A) It has been claimed that a similar phenomenon holds for the Ebbinghaus illusion as well (i.e., the circle surrounded by smaller projected size features appears not only larger, but also nearer).

The overall tendency for Row (1) is that the target in the region of the visual field with smaller projected sizes appears to have greater projected size, greater projected speed, lower luminance contrast, lower distance from the observer. These empirical tendencies are consistent with the predictions from Table 1 because, in each case, the target in the region of the visual field with smaller projected sizes will change in these ways (relative to the change for the other target) in the next moment were the observer moving in the probable direction.

3.6. Row (2): Illusions due to projected speed

Row (2) possesses illusions that are due to one part of the visual field having lower projected speeds than the other, thereby making it probable that the direction of motion is in that part of the visual field.

The central phenomenon in **class 2A** (projected speed affects perceived projected size) is that slower moving objects appear to have greater projected size, and this is what the figure represents. The other subclass can be explained as follows: Longer presentation times are interpreted by the visual system as lower projected speeds (Katz, Gizzi, Cohen & Malach, 1990; Treue, Snowden & Andersen, 1993), and we therefore expect longer presentation time to elicit perceptions of greater projected size, or lower spatial frequency.

Class 2B (projected speed affects perceived projected speed) is comprised by motion contrast, which the figure depicts.

As in class 2A, one illusion subclass in **class 2C** (projected speed affects perceived luminance contrast) concerns the length of presentation time: longer presentation times elicit perceptions of lower luminance contrast. The other subclass is due to lower speed moving surrounds, which lead to lower perceived luminance contrast (Takeuchi & De Valois, 2000). That is, lower speed moving surrounds

suggests that that region of the visual field is nearer to the direction of motion (via (2) of Table 1), and thus a target in that region of the visual field will undergo, in the next moment, a greater percent decrease in luminance contrast (via (C) of Table 1). The figure depicts a generic stimulus for this class.

In **class 2D** (projected speed affects perceived distance), motion-parallax defined depth has been found to induce depth contrast. For example, if a rectangle is lying in the observer's fronto-parallel plane, but the left side is surrounded by lower speeds than the right, then the left side of the rectangle most likely lies in a part of the visual field with greater distances, and is thus nearer to the direction of motion, and distances in that part of the visual field with undergo greater decrease in the next moment. This illusion class could just as well have been placed within class 4D (distance affects perceived distance), since motion-parallax is a cue to distance.

Consistent with the predictions from Table 1, the overall tendency for Row (2) is that the target in the region of the visual field with lower projected speeds appears to have greater projected size, greater projected speed, lower luminance contrast, lower distance from the observer. That is, lower projected speeds have the same perceptual effects as lower projected sizes (which is what one might expect, as discussed Subsection 3.1).

3.7. Row (3): Illusions due to luminance contrast

Row (3) possesses illusions that are due to one part of the visual field having greater luminance contrasts than the other, thereby making it probable that the direction of motion is in that part of the visual field.

The first two subclasses mentioned in the table for **class 3A** (luminance contrast affects perceived projected size) concern the effects of luminance contrast on the classical geometrical illusions: greater luminance contrast enhances the illusions, and equiluminance eliminates them. The second two are cases where greater luminance contrast elicits perceptions of greater projected size (as in the figure) or lower proximal spatial frequency. (The increase in projected size seems to be enhanced more when the object is high luminance and the background low luminance, rather than vice versa, which is the irradiance illusion. This asymmetry we cannot yet explain within this framework.) The last subclass here concerns repulsion (see the earlier discussion

Subsection 3.1), where line segments with greater contrast induce greater perceived repulsion relative to nearby lines.

The central phenomenon in **class 3B** (luminance contrast affects perceived projected speed) is that objects of higher contrast appear to move faster (sometimes called the Hess effect, which the figure depicts). It even works in depth (Brooks, 2001). A second kind of illusion falling within this class is where higher contrast moving surrounds induce greater motion in a target. Finally, because greater contrast leads to greater perceived relative speed, and because greater perceived relative speed means less capture (see Subsection 3.2), we expect and it is known that greater contrast elicits less perceived motion capture.

Class 3C (luminance contrast affects perceived luminance contrast) consists of "luminance contrast contrast," where the perceived luminance contrast of a target is reduced when surrounded by high contrast objects. The Chubb illusion is a famous example, and a similar kind of illusion is pictured.

For **class 3D** (luminance contrast affects perceived distance) the prediction from Table 1 expects that a target in a region of the visual field with greater contrasts should (being probably nearer to the direction of motion) tend to undergo, in the next moment, a greater decrease in distance (and thus distance should be disproportionately perceptually underestimated compared to targets in low contrast regions of the visual field). Note that the fact that greater contrast targets appear nearer than low contrast targets is *not* an illusion falling within class 3D. The latter phenomenon is simply due to the fact that high contrast objects typically *are* nearer. Predicted class 3D illusions are cases where the cues suggest that the two targets are at *identical* distance, but where, nevertheless, one appears nearer due to cues that it is nearer the direction of motion (and thus will become nearer than the other target in the next moment). One possible phenomenon that may be within this class is the lack of perceived depth in equiluminant displays (Livingstone & Hubel, 1987); we are, however, not convinced it is an appropriate instance of this class, since although it demonstrates that perceived distance differences are eliminated at equiluminance, it does not show that perceived distance is disproportionately underestimated in high-contrast regions of the visual field. The figure shown in 3D *is* an example expected illusion within this

class; the uniformly gray rectangle is probably in the observer's fronto-parallel plane (because the target is projecting rectangularly rather than obliquely, and is uniformly gray), and yet it appears that the left end of the rectangle is nearer to the observer because of the higher contrast surround on the left. This is an example of a new illusion made on the basis of predictions by the theory.

The overall tendency for Row (3) is that the target in the region of the visual field with greater luminance contrasts appears to have greater projected size, greater projected speed, lower luminance contrast, lower distance from the observer, and this is consistent with the predictions from Table 1. Greater luminance contrast, then, has the same perceptual effects as lower projected sizes and speeds (which one might expect from the inverse relationship between projected speed and luminance contrast, see Subsection 2.4).

3.8. Row (4): Illusions due to distance

Row (4) possesses illusions that are due to one part of the visual field having greater distances than the other, thereby making it probable that the direction of motion is in that part of the visual field. For the figures in this row we have used binocular disparity to cue relative distance, but any cue to relative distance could be used.

The central subclass of illusion in **class 4A** (distance affects perceived projected size) is where objects in stereograms made to be farther away are overestimated in projected size (as in the figure). Two other classes concern progressive overestimation of projected size as objects are moved farther away, and there is evidence that both accommodation and convergence can elicit this effect.

We have found no illusions in the literature falling explicitly within **class 4B** (distance affects perceived projected speed), but, as discussed Subsection 3.1, the existence of such illusions might be expected to follow from the existence of illusions of class 4A. For example, if the two segments in the figure in class 4A are the paths traveled by two objects over a unit period of time, then the object on the left must appear to be moving faster since it travels over a greater perceived projected distance over that time.

The predictions from Table 1 are that **Class 4C** (distance affects perceived luminance contrast) should possess illusions of the kind in the figure,

where the farther-away (left) part of the slanted-away rectangle should be perceived as lower in contrast than the nearer (right) part of the rectangle. We have found no existing illusions of this kind in the literature, and leave it here as a prediction to test in the future.

Finally, predictions from Table 1 are that **class 4D** (distance affects perceived distance) should possess illusions of depth contrast, which are well known (and the figure provides an example, where the left side of the fronto-parallel rectangle appears to be nearer).

The overall tendency for Row (4), then, is that the target in the region of the visual field with farther-away objects appears to have greater projected size, greater projected speed, lower luminance contrast, lower distance from the observer, and this is consistent with the predictions from Table 1. Greater distance from the observer has the same perceptual effects as lower projected sizes, lower projected speeds, and greater luminance contrasts.

3.9. Row (5): Illusions due to eccentricity

Row (5) possesses illusions that are due to foveation on one part of the visual field, thereby making it probable that the direction of motion is in that part of the visual field. The little eye in the figures of this row represents which side, left or right, is fixated.

The most studied subclass of illusion of **Class 5A** (eccentricity affects perceived projected size) is that objects with lower eccentricity are perceived to have greater projected size. This is related to the second kind of illusion mentioned in this class, which is that it has been observed since Helmholtz that if one looks at a large grid of vertical lines, one perceives the vertical lines to bow away from the point of fixation. This latter effect can be viewed as a kind of "foveal repulsion," which is listed more generally as the third subclass here. Recording foveal repulsion here in class 5A is seemingly at odds with a literature arguing that there is, on the contrary, foveal attraction (e.g., Mateeff & Gourevich, 1983; Müsseler, van der Heijden, Majmud, Deubel & Ertsey, 1999; Eggert, Ditterich & Straube, 2001; Sheth & Shimojo, 2001; Kerzel, 2002b). There is, however, another interpretation to the foveal-attraction studies that accords with foveal-repulsion. We illustrate our alternative interpretation here only for the research of Mateeff and Gourevich (1983).

These researchers had observers fixate on the center of a reference scale, a dot was then briefly flashed at some position in the observer's periphery alongside the reference scale, and the observer's task was to report the value of the reference scale where the flash occurred. They found that observers reported reference scale values nearer to the fixation point than the actual location of the flashed dot. They interpret this as a foveal attraction of the dot, but the experiment is also consistent with the hypothesis that the projected position of the flash is veridically perceived (analogous to the flash-lag effect), and that the *reference scale* is perceptually *enlarged*—a case of foveal repulsion of the reference scale. (This is why we have recorded Mateeff and Gourevich as evidence consistent with foveal repulsion in 5A of the table.) On the basis of the fact that perceived projected sizes are greater under less peripheral viewing, we should indeed expect foveal repulsion (see earlier discussion of “repulsion” in Subsection 3.1). Similar interpretation problems confound the results of others, such as Müsseler et al. (1999), who attempt to resolve the ambiguity by a pointing task; however, this imports both short-term memory and motor issues, and it is no longer a purely perceptual phenomenon.

The existence of illusions in class 5A implies the existence of illusions in **class 5B** (eccentricity affects perceived projected speed), and there are, in fact, known illusions in this class. The primary kind of illusion here is that objects appear to have greater projected speed when eccentricity is lower. This phenomenon is true even for stereo motion. Given the relationship between speed and capture discussed Subsection 3.2, we expect less capture at lower eccentricities, and this phenomenon is known.

Class 5C (eccentricity affects perceived luminance contrast) expects that objects at lower eccentricity should appear lower in contrast (e.g., a gray object on a white background should appear to have greater luminance, or be brighter), and there exists evidence for this.

Finally, **class 5D** (eccentricity affects perceived distance) expects illusions where objects at lower eccentricities have a tendency to be perceived as nearer to the observer. Observation of a phenomenon of this kind goes back at least to Helmholtz, who observed that large flat surfaces appear to bulge toward the observer, and architects

have at times created, for example, concave ceilings in such a way that the perceived shape is flat.

The overall tendency for Row (5) is that the target in the region of the visual field that is looked at by the observer appears to have greater projected size, greater projected speed, lower luminance contrast, lower distance from the observer, and this is consistent with the predictions from Table 1. Foveation, then, has the same perceptual effects as lower projected sizes, lower projected speeds, greater luminance contrasts, and greater distance from the observer.

3.10. Row (6): Illusions due to vanishing point (or converging lines)

Row (6) possesses illusions that are due to one part of the visual field being nearer to the vanishing point of converging lines than the other, thereby making it probable that the direction of motion is in that part of the visual field.

Class 6A (vanishing point affects perceived projected size) consists of the classical geometrical illusions (see Subsection 3.2), and a special case is a grid overlaid on a radial display (as in Fig. 1 or as shown in class 6D).

We accordingly expect illusions of **class 6B** (vanishing point affects perceived projected speed) and there exist studies of perceived-projected-speed-analogs of the geometrical illusions, where the projected speeds of objects moving within a static radial display are misperceived.

Table 1 predicts that **Class 6C** (vanishing point affects perceived luminance contrast) should possess illusions where objects nearer to the center of a radial display will be perceived to have lower contrast. For example, for a radial display on a white background, a gray object nearer to the direction of motion should appear brighter. We have found no existing studies explicitly testing this, but in the figure shown here the square at the center of the radial display appears lower in luminance contrast, which provides a case of a successful new prediction.

Finally, the prediction from Table 1 is that **class 6D** (vanishing point affects perceived distance) should possess illusions where objects nearer to the center of the radial display have their perceived distances disproportionately underestimated compared to objects farther from the center of the radial display. We are aware of no existing studies of such a phenomenon, but the illusion pictured in this

case (and the grid illusion in Fig. 1) provides strong support, as observers perceive the center of the grid to bulge. This is another example of a new illusion made on the basis of predictions by the theory.

Consistent with the predictions in Table 1, the overall tendency for Row (6) is that the target in the region of the visual field that is nearer to the vanishing point of converging lines appears to have greater projected size, greater projected speed, lower luminance contrast, lower distance from the observer. Being nearer the vanishing point of converging lines, then, has the same perceptual effects as lower projected sizes, lower projected speeds, greater luminance contrasts, greater distance from the observer, and foveation.

3.11. Row (7): Illusions due to the focus of expansion (or expanding optic flow)

Row (7) consists of illusions that are due to one part of the visual field being nearer to the direction of motion of dynamic optic flow. This row differs from the others in that, while each of the others consisted of just one of the six correlates of the direction of motion listed in Fig. 2c, this row includes stimuli that contain more than one of the six correlates. For example, realistic radially outflowing dots, all by itself, possesses a projected size gradient (namely, higher dot density near the direction of motion), a projected speed gradient (lower speeds near the direction of motion), and converging lines due to motion blur. We include this row because there are kinds of illusions with more realistic optic flow cues consisting of more than one of the six correlates, and we need a place to record them. The four illusion “classes” here are, therefore, not classes in quite the same sense as the earlier ones (namely, they are more general classes, consisting of potentially more subclasses).

Class 7A (focus of expansion affects perceived projected size) possesses at least five subclasses. The first concerns illusions showing that radial outflow within the boundaries of an object can, under certain conditions, capture the object’s boundaries and elicit an increase in perceived projected size. The second subclass is related to the first, but concerns “flow repulsion” (recall the equivalence between projected size perceptions and repulsion phenomena): flowing backgrounds can repulse the perceived position of an object in the direction of the flow. The third subclass here consists

of illusions where contracting flow is used to induce perceived forward motion toward stimuli, and observers perceive the stimuli to undergo expansion. A fourth class refers to the bulging grid shown in 7D (focus of expansion affects perceived distance): in addition to observers perceiving the grid to bulge when the observer looms toward it, we have also observed that its straight contours are perceived to bow in a manner like that shown in the figure in box 6D of Table 2 (and in the grid of Fig. 1). Another subclass here we call the “dynamic Zanker-Hering analog,” and it refers to the phenomenon that when a straight line segment is moved in a direction normal to its orientation (e.g., a vertical line segment moving horizontally), observers perceive it to be bowed with its center leading the endpoints (Zanker, 2001). A vertical line segment moving rightward implies that the viewer is moving somewhere to the left. In the next moment, the parts of the line nearer the direction of motion—namely the central parts of the line—will experience greater horizontal components of repulsion, and this explains why it bows out away from the direction of motion in a way similar to the perceptual bowing found in the Hering illusion. An illusion related to this class—but one that does not quite fit the criteria—is that of Cai (Cai & Schlag, 2001; Cai & Cavanagh, 2002), where a black vertical line segment is moving rightward, and growing in projected size. At one frame along its traversal, the line segment changes color to red, and changes back to black for the remaining frames. The observer perceives the red line to occur at a position shifted to the right of its actual position, but also perceives it to be larger than it originally projected. Perceiving-the-present naturally expects this as follows. Suppose the “red” frame occurs at time t . What are the probable projected features in the next moment, at $t+100$ msec? Let us assume that the visual system has as evidence with which to make a guess all the frames up to and including the “red” frame. Thus, as far as the visual system is concerned, it has so far received information about an expanding and rightward moving vertical line segment that suddenly turns red in the last frame. It is relatively straightforward to expect that, in the next moment, the line segment will have expanded more and moved further rightward. But it is also reasonable to expect that its color may be the same as it was in the last-seen frame, namely red.

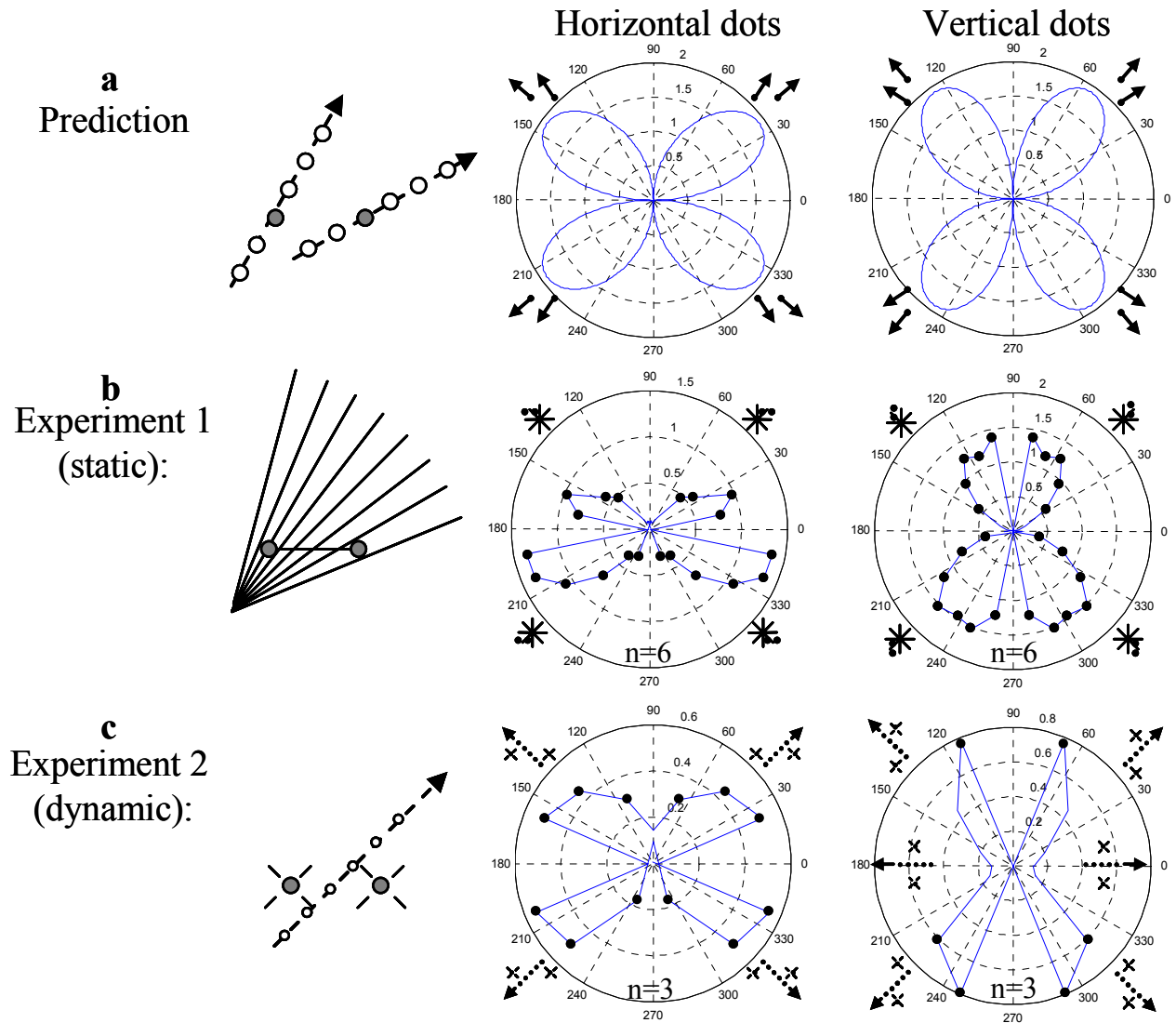


Figure 4
 Predicted illusion magnitude (a) and measured illusions for static (b) and dynamic (c) illusions. (a) The predicted misperception as a function of polar angle around the direction of motion. On the left is a figure conveying the fact that when the two optically flowing dots have the same projected distance from the horizontal meridian (the gray dots), the one nearer the direction of motion will, in the next moment, typically project further from that meridian than the other dot. The “horizontal dots” polar plot in the middle of this row shows how much farther the near-direction-of-motion dot moves away from the horizontal meridian than the far-from-direction-of-motion dot in the next moment, measured as the projected angle made between the horizontal meridian and the imaginary projected line connecting the dots. These predicted values are computed as follows: The midpoint between the pair of horizontal dots is placed on a 1 meter radius circle in the forward-moving observer’s fronto-parallel plane, at a distance of 1 meter in front of the observer. The dots themselves are placed 0.5 meters on either side of the midpoint. The observer is assumed to move at 1 meter per second, and the amount of vertical displacement is computed over a (latency) time interval of 100 msec. These values were chosen somewhat arbitrarily, and the qualitative predictions are not dependent on these values. Analogous computations were made for the “vertical dots” plot, which is similar, but where the dots are above one another, and the issue concerns the next-moment projected distance of the dots from the vertical meridian. (b) and (c). Results for Experiments 1 and 2. The two illustrations on the left in the following two rows describe stimuli that are plausibly due to optic flow projection dynamics of the kind just described in row (a), and each have two gray dots at identical projected distance from the horizontal meridian. (b) is for the static, classical geometrical illusions, and (c) is for a dynamic version of the classical geometrical illusions. Since the near-direction-of-motion dot is, in the next moment, going to be shifted further away from the horizontal meridian, perceiving-the-present accordingly expects observers to perceive the near-direction-of-motion dot to be shifted in this way. The method of adjustment was used for each experiment. For each of these kinds of stimulus, the averaged results are shown for where the dots are horizontally aligned, and where the dots are vertically aligned. In each case the expected illusions exist in each quadrant, showing substantial similarity to the prediction in (a). Illusions are measured in degrees of slant, where the illusion is positive if the dot nearer to the observer’s direction of motion is perceived farther from the meridian than the other dot. Number of subjects, n , is shown in each plot. Corresponding positions in the left and right half of the visual fields have been averaged together; so the left and right side of each plot are identical and redundant. Dots at a point on the graph indicate that the point is significantly greater than zero at the $p < 0.05$ level (via t-test), where an observer’s responses on the left side were treated as independent of his responses on the other side (the degrees of freedom is therefore twice the number of subjects minus two).

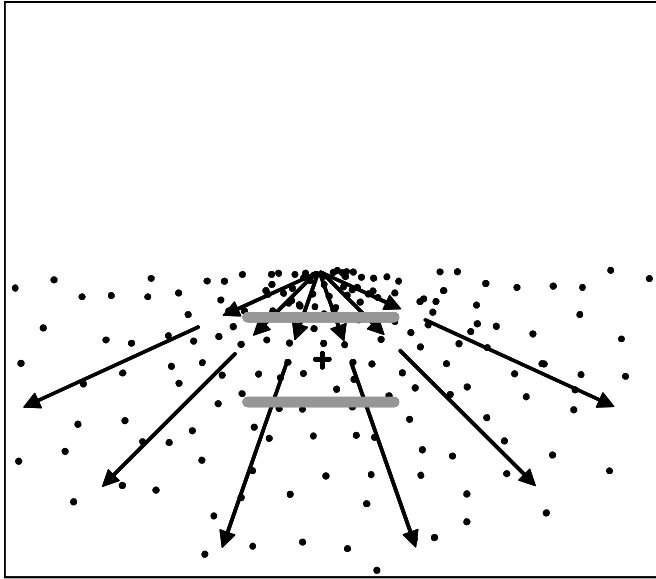


Figure 5
Illustration of an experiment (Dynamic Ponzo-Flash Illusion, Experiment 3) demonstrating that the speed of optic flow modulates illusions as expected, that is, that faster optic flow, consistent with faster forward movement, led to greater illusions (i.e., greater misperceptions that the upper bar has larger angular size than the lower bar). Optically flowing black dots were presented in the lower half of a white screen, simulating forward motion toward the focus of expansion of those dots. Dots flowed only in the hemifield below the focus of expansion. Two simulated observer speeds were used, “slow” and “fast”: dots began with angular speed 0.80 deg/sec in “slow”, and 1.60 deg/sec in “fast” condition; and acceleration 5.39 deg/sec² in “slow” and 10.78 deg/sec² in “fast.” These values were chosen because they led to qualitatively different simulated observer speeds. The observer fixated on a red dot (shown in Fig. 3 as a black cross) 3.34 deg below the focus of expansion. After 3 seconds, two red, horizontal, Ponzo line segments briefly flashed (0.036 seconds) above and below the fixation point (1.90 deg above and below), each below the focus of expansion. In the two-alternative forced-choice design, the projected lengths of the upper and lower Ponzo line segments varied over 7 pairs of values, ranging from upper segment being 6 percent longer than lower segment to lower segment 12 percent longer than upper segment (with center around 4.6 degrees or arc). In total, then, there were 7 kinds of Ponzo-line presentations, and two optic-flow speed conditions, for a total of 14 distinct stimuli. Each of these was presented 10 times, randomly interleaved. After each presentation of the flow followed by the flashed Ponzo lines, observers judged whether the upper or lower Ponzo line appeared larger in projected length. The experiment took about 20 minutes to complete. Ten observers (two non-naïve, eight naïve) participated in the experiment. All observers had normal or corrected-to-normal visual acuity.

Before moving to case 7B, we describe some experiments we carried out that fall into category 7A, and are, intuitively, dynamic classical geometrical illusions.

In the first dynamic experiment we show that manipulating the direction of forward movement using a dynamic stimulus modulates perception as predicted. For two radially outflowing dots starting at the same elevation, Fig. 4a shows how their

elevations differ in the next moment as a function of polar angle around the observer’s direction of motion. For example, if both dots are in the observer’s upper right quadrant as shown in the illustration on the left of Fig. 4a, then in the next moment the left dot will rise higher than the right dot, and this is shown in the upper right quadrant of the “horizontal dots” plot (positive illusion magnitude meaning that the inner dot undergoes greater vertical angular displacement in the next moment). The “vertical dots” plot is analogous, but where dots are above one another and it concerns horizontal displacement. The two plots in Fig. 4a amount to predictions. The “horizontal dots” plot in Fig. 4b shows how observers perceive the relative elevations of two side-by-side dots in a radial display, as a function of polar angle around the radial display (Experiment 1). For example, for the stimulus shown on the left of Fig. 4b, the empirical illusion magnitude is shown in the upper right quadrant of the “horizontal dots” plot, which means that the left dot is perceived to be higher than the right dot. Note that this is consistent with how the elevations of the two dots will change in the next moment, as predicted by Fig. 4a. That is, the two plots in Fig. 4b for static radial line illusions fits the prediction of the forward-motion perceiving-the-present hypothesis. In Experiment 2 the static converging lines of Experiment 1 are replaced by a flowing dot (6 deg/sec), and the two target dots (separated by 5 deg) are briefly flashed (for about 40 msec) just as the flowing dot passes them, illustrated by the figure on the left of Fig. 4c. The plots in Fig. 4c show the average illusion magnitude across all the conditions, and one can see that this dynamic classical geometrical illusion is modulated by direction of motion as predicted (Fig. 4a), and has the same signature as the static geometrical illusion in Fig. 4b.

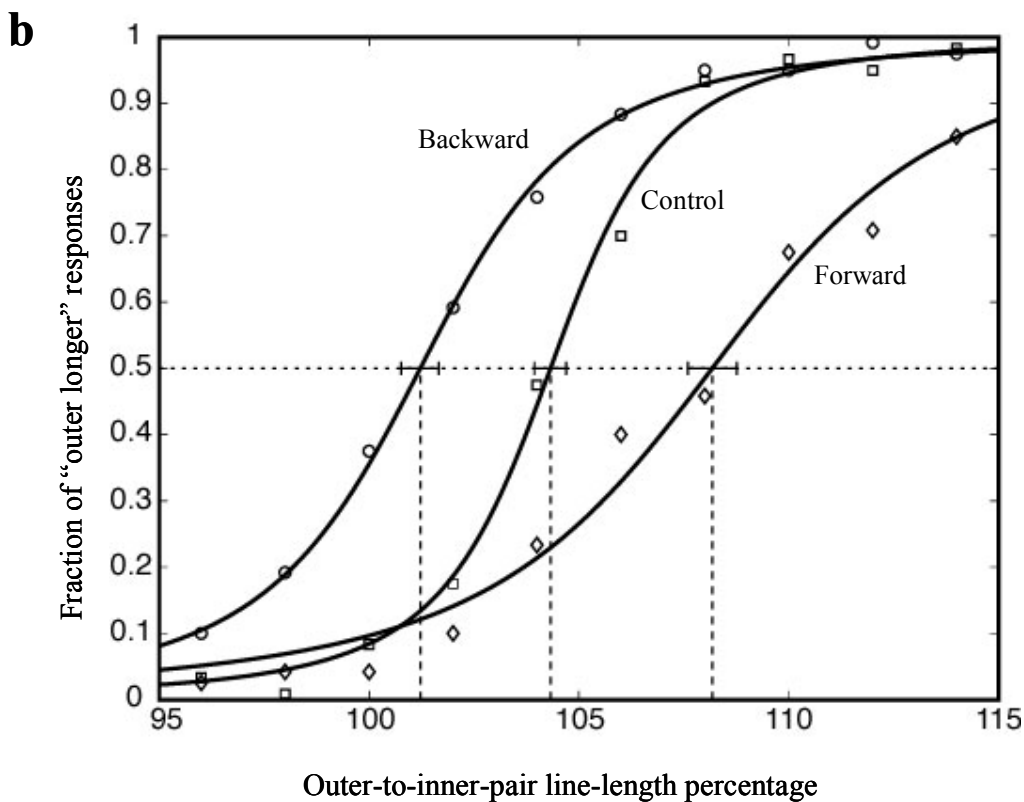
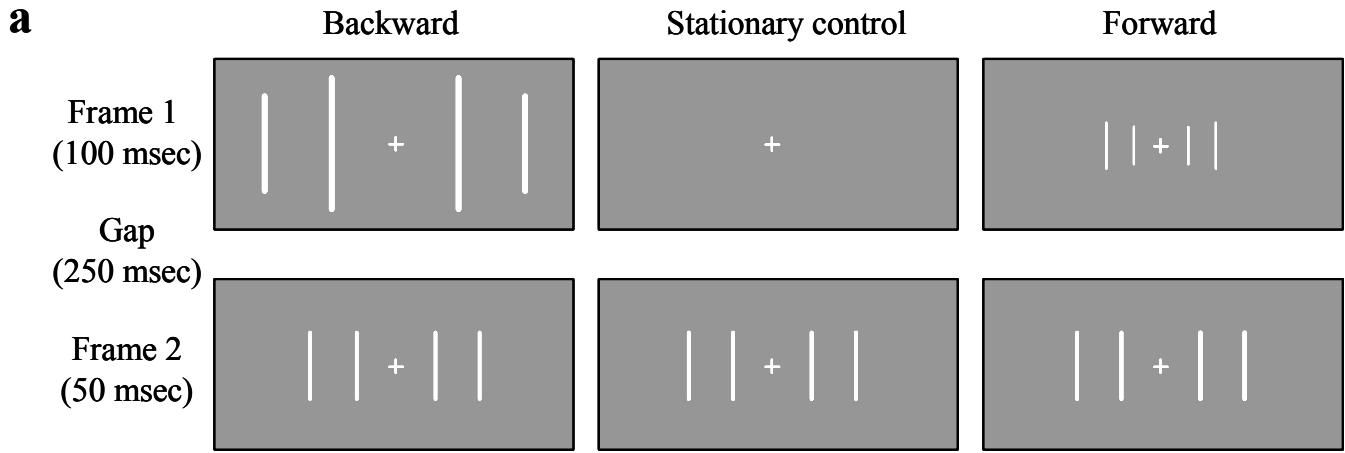


Figure 6

(a) Illustration of the three conditions of Experiment 4, shown in the three columns here. The two rows show the first and second (which is the last) frame of the stimuli. The second frames are identical in all three conditions, and the outer lines of the second frame are varied in the two-alternative forced choice design. In the “stationary control” condition, the first frame has no lines at all. In the “backward” condition, the lines in the first frame are arranged approximately consistent with how they would project if, in the next frame, they receded away from the observer and projected as in frame 2. And in the “forward” part, the lines in the first are arranged approximately consistent with how they would project if, in the next frame, they approached the observer and projected as in frame 2. Observers were required to judge whether the inner lines or the outer lines in the second frame are larger. 10 trials were performed for each setting of the outer line segment’s length, which varies over 11 values. 12 (3 non-naïve, 9 naïve) observers participated in this experiment. (b) Results of Experiment 4, for all 12 observers. The plot shows, for the three conditions, the fraction of “outer is longer” responses versus the relative physical settings of the outer and inner lines (measured here as the outer-to-inner percentage, 100% meaning the outer and inner are the same projected size). In the stationary control condition (squares), observers had to increase the size of the outer pair to 4.3% larger (95% confidence interval, [3.9, 4.7], via standard bootstrap) than the inner pair to perceive them as equal. That is, observers perceived the inner lines to be 4.3% larger than the outer lines. In the forward condition (diamonds) the illusion was significantly enhanced to 8.2% (95% confidence interval, [7.6, 8.8]), whereas in the backward condition (circles) the illusion was significantly diminished to 1.2% (95% confidence interval, [0.8, 1.7]).

Next we investigated whether the inferred speed of forward movement via dynamic optic flow increases misperceptions as expected. In the static domain, this is analogous to adding more converging lines (because when moving faster, a greater number of objects tend to be moving sufficiently fast to induce optic blur), and it is well-known that classical geometrical illusions such as the Ponzo are stronger when there are more converging lines. Fig. 5 illustrates the basic design for our dynamic stimulus, where the bottom hemifield possesses optically flowing dots, and two Ponzo bars are briefly flashed. There were two versions of the flowing dots, “slow” and “fast.” Here we expect, and find, that the upper Ponzo line should be perceived as projecting larger, since it is nearer to the observer’s direction of motion. Points of subjective equalities were computed for each observer on the “slow” and “fast” conditions: the average illusion was 3.9% in the “slow” condition, and 5.6% in the “fast” condition, where a positive value indicates the upper Ponzo line was perceived to project larger than the lower Ponzo line. The amount of illusion was significantly greater in the “fast” condition: the average difference was 1.7% (standard error = 0.52), and this is significantly above 0 by a *t*-test ($p=0.0101$, $t=3.24$, $df=9$). On an observer-by-observer basis, 9 of the 10 observers perceived a greater illusion in the “fast” condition than the “slow” condition.

It is useful to investigate one related kind of experiment that may be deemed an appropriate test of our theory: backward motion (see Changizi & Widders, 2002, for discussion of this). The reader may wonder, for example, if optical contraction consistent with backward motion should lead to a counter-Ponzo illusion in the dynamic Ponzo-flash experiment (of Experiment 3). However, we feel that this type of experiment may only be a weak test of our theory. The visual system can be expected to be competent at perceiving-the-present only under conditions that are sufficiently similar to the natural conditions of stimulation, either evolutionarily or during the animal’s lifetime. Backwards motion is quite infrequent. Furthermore, when moving backwards one is not at risk of colliding into objects in one’s view. These facts together suggest that there is less selective pressure for perceiving-the-present mechanisms designed for backward motion. There is therefore reason to doubt that the visual system might be able to correct for latencies under backward-

motion conditions. Nevertheless, it would be interesting to see whether the visual system can sometimes appropriately respond to backward motion stimuli. Experiment 4 describes a very simple kind of backward motion stimulus, but one that nevertheless possesses abundant cues indicating that the target objects are receding away from the observer. Abundant cues are probably necessary for the “backward” interpretation because of its relative infrequency (Lewis & McBeath, 2004), similar to the bias against a “backward” interpretation of other objects (Tinbergen, 1939, 1951; McBeath, Morikawa & Kaiser, 1992; Pavlova et al., 2002). This experiment consisted of three conditions: “stationary control,” “backwards,” and “forwards.” See Fig. 6a for illustration. In each condition, each trial presented two frames in short succession, and in each frame (except the control) there were four vertical line segments, horizontally aligned—two to the left of fixation (left pair) and two to the right (right pair). In each condition, the lines in the second frame are identical (and is akin to the Ponzo, but one on each side of the center, and without the converging lines); only the first frames differ, and differ so as to indicate backward motion, forward motion, or to serve as a control. Observers were asked to judge whether the inner lines or the outer lines in the second frame are larger. In the stationary control condition, observers perceived the inner pair of lines to be 4.3% larger (95% confidence interval, [3.9, 4.7], via standard bootstrap) than the outer pair, consistent with the effects of eccentricity alone (see case 5A of Table 2). In the forward condition, the illusion was significantly amplified to 8.2% (95% confidence interval, [7.6, 8.8]). In the backward condition, the illusion was significantly diminished compared to the control, namely 1.2% (95% confidence interval, [0.8, 1.7]). That is, compared to the control, forward and backward motion modulate the illusion in the expected directions (Fig. 6b).

Class 7B (focus of expansion affects perceived projected speed) is expected from the existence of 7A illusions. Some looming illusions fall within this class, such as the “color-balls” of Widders & Changizi (2001), which are simply circles with a radial color gradient (Changizi, 2003), where looming toward the center of the circle elicits a perception of the inner colors flowing outward, filling the circle; the inner colors seem to overtake the outer colors. We also mention here an illusion that does not quite fit

properly into the table, but is closely related to class 7B: expanding flow appears faster than rotating flow (Geesaman & Qian, 1996). This is expected since radial flow tends to accelerate in the next moment, but rotating flow does not.

The predictions from Table 1 are that **Class 7C** (focus of expansion affects perceived luminance contrast) should have illusions where, for identical-speed objects flowing out in an observer's visual field, the one nearer to the direction of motion should be perceived as lower in luminance contrast. We have found no existing evidence in the literature for this under optic flow conditions, but the class 2C (projected speed affects perceived luminance contrast) research by Takeuchi and de Valois (2000) provides indirect support.

Class 7D (focus of expansion affects perceived distance) is exemplified by the bulging grid, which is shown. It has also been shown that, using stereo displays, dots flowing toward an observer can sometimes capture an object and decrease its perceived distance from the observer.

The overall tendency for Row (7) is that the target in the region of the visual field that is nearer to the focus of expansion appears to have greater projected size, greater projected speed, lower luminance contrast, lower distance from the observer. Being nearer the focus of expansion, then, has the same perceptual effects as lower projected sizes, lower projected speeds, greater luminance contrasts, greater distance from the observer, foveation, and being nearer to the vanishing point of converging lines.

3.12. The empirical regularity

Although we can make no quantitative claim concerning the exhaustiveness of this literature search, Table 2 possesses over 150 citations, the result of searching through on the order of one thousand papers. In a few illusion classes (3D, 4B, 4C, 6C, 6D and 7C) we have found no existing research looking into the kind of stimuli about which the prediction concerns; in some of these cases the figure shown in Table 2 serves as a demonstration of the predicted phenomenon, but in other cases (the ones with question marks) it is left for future study. However, the powerful conclusion of the metareview is that, *for each of the remaining 22 illusion classes, the central phenomenon found in the literature accords with the prediction from Table 1.* That is, the

predicted pattern of illusions from Table 1 is largely confirmed by this study. For 28 categories, there are $2^{28} \approx 270$ million possible empirical patterns (assuming that each category has an illusion either in the predicted direction or in the opposite direction), and evidence points to the conclusion that the empirical pattern fits just one of these 270 million possible patterns, namely the predicted pattern from Table 1. (Or, for the currently known pattern across the 22 illusion classes mentioned, this amounts to one in approximately four million.) In total, the empirical regularity (not a universal law, see Subsection 2.9) is as follows:

A target in a region of the visual field with...

(1) smaller sizes, (2) slower speeds, (3) greater luminance contrast, (4) farther distance, (5) lower eccentricity, (6) greater proximity to the vanishing point, or (7) greater proximity to the focus of expansion,

will be perceived to have...

(A) greater perceived projected size, (B) greater perceived projected speed, (C) lower perceived luminance contrast, and (D) lower perceived distance from the observer.

Our hypothesis from Section 2, Table 1, predicts exactly this. More specifically, this empirical regularity is explained because the optic-flow-regularities hypothesis predicts that

A target in the region of the visual field...

toward which the observer is moving

will undergo in the next moment a greater...

(A) increase in projected size, (B) increase in projected speed, (C) decrease in luminance contrast, and (D) decrease in distance from the observer.

And importantly, stimulus features (1) through (7) are cues to the observer's direction of motion, as discussed in Subsection 2.4. ...*this* is what these seven features share in common.

4. Conclusion

Here we have examined the hypothesis that the visual system possesses mechanisms that attempt to compensate for neural delays while in ecologically typical forward motion. In the first half of the paper

we derived a 7 by 4 matrix of predicted illusion classes (Table 1), amounting to the prediction of a broad *pattern* of illusion across four perceptual modalities, and due to seven kinds of stimulus features. In the second half of the paper we presented evidence via a survey of the visual perception literature that this pattern of illusions appears to exist (Table 2). Because our optic-flow-regularities hypothesis was originally developed with only the classical geometrical illusions in mind (Changizi, 2001, 2003; Changizi & Widders, 2002)—which amount to just one of the 28 illusion classes—the success of the general prediction amounts to a predictive success story for the optic-flow-regularities hypothesis, and for perceiving-the-present more generally.

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APPENDIX for Changizi et al., “Systematization...”

Appendix A: Projected versus distal properties

Important for understanding our paper is the distinction between the perception of distal properties versus the perception of projected properties. *Distal properties* are features of the objects out there in the world. For example, the height of a tree (measured in meters) is a distal property, as is the surface reflectance (or lightness) of an object. *Projected properties*, on the other hand, concern only the nature of the light projected toward an observer at his/her particular location (not to be confused with the retinal projection, although sometimes the retina may veridically record projected properties). For example, how much of the visual field is filled by a tree (measured in degrees, i.e., the angular size of the tree) is a projected property, as is the amount of light projected toward the eye (or brightness) from an

object. It is useful to think of an imaginary projection sphere around a person’s eyes, where the projection sphere lacks distance information: projected properties are then properties measurable on this sphere. Projected properties are important properties to perceive (in addition to distal properties) because it is useful to perceive where things are in one’s visual field (i.e., in which direction around oneself is an object), and once one is able to perceive where things are in one’s visual field, the perception of projected size and speed follow, because the former is just the projected distance (or visual angle) between two points in the visual field, and the latter is just the projected distance swept by a moving point during a unit time interval.

This “distal versus projected” distinction has been made often in the visual perception literature (Gibson, 1950; Gilinsky, 1955; Carlson, 1960; Mack, 1978; Rock, 1983; Arend & Goldstein, 1990; Sedgwick & Nicholis, 1993; Gillam, 1998; Palmer, 1999; Changizi and Widders, 2002), and perception of projected size (as opposed to distal size) has been observed a number of times over the history of visual perception (Reid, 1813; Joynson, 1949; Gibson, 1950; Gilinsky, 1955; Jenkin & Hyman, 1959; Over, 1960; Carlson, 1960, 1962; Biersdorf, Ohwaki & Kozil, 1963; Rock & McDermott, 1964; Ono, 1966; Baird, 1968; Craig, 1969; Leibowitz & Harvey, 1969; Lucas, 1969; Daniels, 1972; Foley, 1972; Angell, 1974; Komoda & Ono, 1974; Mack, 1978; McCready, 1965, 1985, 1986; McKee & Welch, 1989, 1992; Sedgwick, 1986; Sedgwick & Nicholis, 1993; Plug & Ross, 1994; Gogel & Eby, 1997; Kaneko & Uchikawa, 1993, 1997). Researchers have also shown that observers make qualitatively very different “size” judgments when given projected size instructions compared to when given distal size instructions (Gilinsky, 1955; Jenkin & Hyman, 1959; Carlson, 1960, 1962; Biersdorf et al., 1963; Leibowitz and Harvey, 1969): for stimuli with cues to the distal size, projected size instructions lead to judgments closely matching projected size, and distal size instructions lead to judgments closely matching distal size. Most of the literature on motion perception also recognizes the perception of projected properties, since perceived speed is nearly always measured in degrees/second. Furthermore, McKee and Welch (1989, 1992) provide evidence that discrimination for projected size and speed is often better, and never worse, than for distal size and speed. (Burbeck, 1987, finds poorer proximal

spatial frequency discriminations than distal, but see the discussion in McKee & Smallman, 1998). Measurements of perceived lightness (distal) versus perceived brightness (projected) have also been made (see Arend & Goldstein, 1990).

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