STARTREK ILLUSIONS DEMONSTRATE GENERAL OBJECT CONSTANCY

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ABSTRACT OF DISSERTATION

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Abstract

Size constancy is a well-known example of perceptual stabilization accounting for the effect of viewing distance on retinal image size. In a recent study (Qian & Petrov, 2012), we demonstrated a similar stabilization mechanism for contrast perception and suggested that the brain accounts for effects of perceived distance on various other object features in a similar way, a hypothesis that we called General Object Constancy. Here we report new illusions of depth further supporting this hypothesis. Pairs of disks moved across the screen in a pattern of radial optic flow. A pair comprised either a small black disk floating in front of a large white disk, creating the percept of a pencil tip viewed head on (thus called the ‘pencil’ stimulus), or a white disk floating upper left to a black disk, creating the percept of a white disk casting a shadow (thus called the ‘shadowed disk’ stimulus). For the ‘pencil’ stimulus, as the ‘pencils’ moved away they appeared to grow in contrast, in diameter, and to be getting sharper; for the ‘shadowed disk’ stimulus, as the disks moved away they also appeared to grow in contrast, and to be separating farther away both laterally (size illusion) and in depth. The contrast and size illusions replicated our previous findings, while the depth gradient (sharpness) illusion and the depth separation illusion manifested a depth constancy phenomenon. We discovered that depth and the size constancies were related, e.g., the size illusion and the depth gradient/separation illusions were strongly correlated across observers. On the one hand, the illusory diameter/separation increase could not be canceled by any degree of depth modulation. On the other hand, decreasing the diameter of the pencils during optic flow motion (thus increasing their disparity gradient) could affect the illusory depth gradient increase; decreasing the separation between the disks and their shadows during optic flow motion could cancel or even reverse the illusory depth separation increase. These results are explained by the General Object Constancy model: besides
using the same scaling factor to account for size, contrast, and depth variations with viewing distance, the brain uses the apparent object size to additionally scale contrast and depth signals to yield the perceived contrast and depth.
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Chapter 1: General Introduction

Perceptual constancy is a crucial characteristic of vision. Human need to construct a stable and meaningful representation of objects out in the world in order to identify, utilize and interact with them, therefore to survive and live better. How is this stable and meaningful representation obtained? The information directly available to the visual system is from the retinal images. However, they undergo continuous variations due to the changes in the environment or interactions with the environment. For example, when the angle of perspective, distance, or lighting changes, the retinal image, and hence the sensation of an object changes, including its shape, size, and color. Constancy allows us to see an object as having consistent features, even though our sensation of that object undergoes variations. Here is a well-known passage in which Husserl described perceptual constancy:

_Here it is enough to point to the readily grasped distinction between the red of this sphere, objectively seen as uniform, and the indubitable, even necessary adumbration (Abschattung) of subjective color sensations in the perception itself — a distinction repeated in relation to all kinds of objective properties and their corresponding complexes of sensations._ (Husserl & Moran (2001), LU V 2 Findlay trans.)

While Husserl was concerned with the way we see constant features despite variation in our experiences of those features, in empirical psychology, perceptual constancy generally refers to that a representation of a feature remains invariant despite variations in the stimulus. As James J. Gibson have described, an invariant feature is the “non-change (in perception) that persists during change (in view or in illumination)” (Gibson, 1950). The change in the stimulus is
described in the terms of physical properties, such as variation in wavelength of light (Goldstein, 2002), or variation in viewing distance. Indeed, visual constancy phenomena can be coarsely divided into two categories based on these two factors: 1) constancies under changes of illumination, such as lightness and color constancies; 2) constancies under changes of egocentric distance or relative object-self position, such as size and shape constancies. Besides the listed above, there are many other less well-known yet equally important constancy phenomena, such as depth constancy and contrast constancy, all of which we will discuss later in detail.

Constancy phenomena are closely related to perceptual illusions. Despite our reliance on the constancy mechanisms to stabilize the visual information associated with variations in viewing conditions to recognize objects and to perceive a consistent world, these mechanisms sometimes can induce visual illusions. An illusion is a distortion of the senses, usually due to general assumptions the brain makes during perception. These assumptions are made using common sense or organizational principles under normal viewing conditions, like Gestalt, an individual’s experience of depth perception (same object with a smaller size is farther away), etc... Presumably, the same mechanism that preserves a constancy phenomenon would trigger a corresponding illusion, when manipulations of visual stimuli are made to contradict the observations in natural scenes. Therefore, whenever there is a constancy phenomenon, there is an associated illusion. Studying the visual illusions may reveal how the brain normally organizes and interprets visual stimulation to achieve perceptual constancy.

The purpose of the thesis is to study the relation of several constancy phenomena. In this chapter, we will demonstrate several types of constancies and their related illusions, mainly focusing on the second category: constancies under changes of viewing distance. To this end, first we will describe how different cues contribute to distance perception, and then will discuss
constancy phenomena and their corresponding visual illusions.

1.1. Distance perception

One of the oldest and classic problems in philosophy and psychology is perception of distance. It refers to seeing and recognizing distances between two points in space in any direction relative to an observer. Distance perception is essential to three-dimensional space perception, thus it plays an important role in the control of many of human spatial behavior. For example, studies found that blind walking to a target after viewing the target was quite accurate (Loomis et al., 1996). Human can undoubtedly make judgments of distance fairly accurately, since our everyday life relies on such accurate distance perception. However, the question is, given two-dimensional retinal images of an object, how can one perceive the distance between oneself and the object?

Could optical information from the retinal image be used to calculate the distance? Berkeley (1709) noted that a point in space projects to a point on the retina and that this retinal projection conveys no information about the point’s distance from the eye. Thus, he concluded that distance perception could not be solely based on retinal information. Even though perception of distance is more accurate under binocular viewing conditions than that under monocular viewing conditions (Granrud et al., 1984; Bingham & Pagano, 1998), there is no question that we can still perceive depth quite well in photographs and drawings. This is because there are many other depth cues to distance in complex natural or near-natural scenes. We will discuss these cues in the following section.
1.1.1. Depth cues

The sources of information about depth are often referred to as cues to depth. These cues can be divided into two broad categories, extra-retinal cues and retinal cues. The extra-retinal cue, also known as the oculomotor cue, derives from the act of muscular contraction of either the muscle fibers controlling the focus of the lens or the fibers controlling the positions of the eyes. The retinal cue, also known as the visual cue, is obtained from the visual information on retina. It can be subdivided into binocular cues and monocular cues. Figure 1 summarizes those cues in a tree graph.

Oculomotor cues.

Oculomotor cues arise from muscular responses – accommodation, and adjustments of the eye – vergence. These cues are generally effective only in a short range, and not very
Accurate (Leibowitz & Moore, 1966; Wallach & Floor, 1971).

**Accommodation**

Accommodation is a process where the shape of the lens changes in order to keep the retinal image in clear focus (Dalziel & Egan, 1982). Distant objects can be clearly focused on the retina by flattening the lens, also known as relaxed accommodation. Feedback of the change of tension on the ciliary muscles provides extra-retinal information about viewing distance. On the other hand, if an object is out-of-focus, the amount of blur can serve as a cue to relative depth. It has been shown that in absence of all the other depth information, observers could judge that two spots of light presented in complete darkness are at different distances at the same time. Presumably because accommodation cannot correct for both of the lights at the same time, resulting one of the lights blurred and out of focus, suggesting that the lights are at different depth planes (Kaufman, 1974).

Accommodation is a short-range cue. Human sensitivity for defocus is roughly 0.2 - 0.4 diopter under optimum conditions, so accommodation in force is constrained to 2 m or less (Campbell, 1957).

**Convergence and Divergence**

Another oculomotor cue is vergence, a movement in which the eyes move in different directions. Convergence is an inward rotation of the eyes when an object moves closer; divergence is an outward rotation of the eyes when an object moves farther away. Muscle contractions regulate the convergence angle, and its feedback can provide distance information. It is a relatively weaker depth cue since the brain uses other depth cues preferably to adjust the
eye (Takeda et al., 1999; Enright, 1987). In addition, a number of studies found that vergence signals cannot provide veridical stereoscopic depth (Johnston, 1991; Collett et al., 1991). Nevertheless, Mon-Williams et al. (2000) suspected these findings might result from using stimuli (usually random dot paradigm) that by nature had ambiguous depth information. They re-examined the role of vergence in the maintenance of stereoscopic depth constancy for real three-dimensional objects, and suggested that vergence could provide a veridical interpretation of depth. Furthermore, Tresilian & Mon-Williams (2000) found that convergence information is given a greater weight when it is consistent with other depth cues.

Convergence is potentially the most powerful cue to distance perception. It also works in a short range: some researchers found it effective at most 2 meters (Ono & Comerford, 1977), while other stated it to be not very useful beyond 8 meters (McKee & Smallman, 1998). The precision of convergence judgments is about 5 arcmin at 4 m, or roughly 10% of the convergence angle (Foley, 1980).

Visual cues.

Visual cues have two subcategories, monocular and binocular cues. Monocular cues are often known as pictorial cues, because they are available in pictures with one eye viewing. Motion parallax is another kind of monocular cue that emerges from the relative motion between the target and observer.

Perspective

Linear perspective is a well-known depth cue that was used during the fifteenth century by Italian artists. It refers to the convergence of parallel lines that extend infinitely in distance. It
is a powerful long-range depth cue that can override the contradictory retinal disparity cue that results from the picture actually being flat (Wallach & Zuckerman, 1963; O’leary & Wallach, 1980).

*Texture gradients* is a combination of linear perspective and relative size cue. James J. Gibson first put an emphasis on texture gradient cue (Gibson, 1950, 1966, 1979), and noted that it provides precise information about distance. Sinai et al. (1998) found that observers were quite accurate judging distance as long as the ground plane has uniform texture, but they overestimated the distance when the texture plane was abruptly disrupted.

*Aerial perspective* emerges from the fact that the air is filled with light-absorbing and light-scattering particles even on the clearest of days (Coren et al., 2004). The light from more distant objects must travel through the atmosphere for a greater distance and may be subject to increase absorption or scattering of the light by the particles in the air. Therefore, a distant object may appear to be slightly bluer or less pronounced than a nearer object that is physically of the same color (Ross & Plug, 1998). It is also referred to as relative brightness or relative contrast (Coren et al., 2004), because a more distant object may appear to be less bright, or lower in relative contrast. The brighter of the two identical objects is tend to be judged as closer in the absence of other cues; even when other cues are available, reduced contrast is associated with judging objects as more distant (Rohaly & Wilson, 1999; O’Shea et al., 1994). In the absence of contrast reduction, blur can also serve as a depth cue (O’Shea & Govan, 1997).

**Occlusion**

Because a near object can block the view of a farther object, occlusion specifies which object is in front of the other, but not the distances separating them. However, it is a strong depth
cue that it can override retinal disparity when the two cues are in conflict (Kaufman, 1974).

**Size**

As an object moves farther away, its retinal image size diminishes – retinal size cue to depth. Another size cue is familiar size – it relies on the knowledge of the dimensions of a recognized object to provide a distance scale. It is an effective cue to depth in absence of other information (Ittelson, 1951), not only relative depth, but also absolute depth (Fitzpatrick et al., 1982; Marotta & Goodale, 2001).

**Shading and shadows**

Shading and shadows can provide a strong cue to depth. It relies on the knowledge or presumptions about the location of the light source, but is made reference to head orientation, not gravitational orientation (Howard et al., 1990). Kersten et al. (1997) found that perceived depth varies depending on the position of a shadow relative to the object casting the shadow. A compelling illusion of depth based on this cue occurs where a stationary target shape seen against a checkerboard pattern can be made to appear to move toward and away from the observer by laterally moving a cast shadow toward and away from the target (Kersten et al., 1996).

**Motion parallax**

When the head or body moves, objects at different distances move at different directions and speeds on the retina, an effect known as motion parallax. It is fairly accurate for relative distance estimation (Landy et al., 1995; Rogers & Cagenello, 1989), but is not very good for absolute distance (Bradshaw et al., 2000). If the motion is self-generated, so that the observer has
some way of calibrating relative speed, motion parallax can be a robust cue to distance (McKee & Smallman, 1998). Optic flow is often deemed as an instance of motion parallax.

**Binocular depth cues**

Binocular depth cues, also known as stereopsis, allow us to judge relative depth with great accuracy. Retinal disparity, that is, the difference in lateral separation between objects as seen by the left eye and by the right eye, can be used to judge the absolute distance. Relative disparity, that is, the difference in the disparity of two objects, can be used to judge the distance separating objects. However, the latter depends on the estimated viewing distance, because, for example, 5 min of disparity at a viewing distance of 1 meter corresponds to a much smaller distance separation than 5 min of disparity at a viewing distance of 5 meters. Therefore, inaccuracies in estimating distance from other depth cues could affect the accuracy of relative disparity judgment (Foley, 1980). Johnston (1991) found that a three-dimensional shape defined by disparity appeared to be thicker or flatter in depth at different viewing distances.

Although retinal disparity cues at very large observation distances are often assumed to be ineffective, most of these studies have not directly examined this question and thus the conclusion is suspect. Palmisano et al. (2010) investigated stereoscopic perception of real depths at large distances. They presented pairs of light targets either in complete darkness or with the environment lit as far as the observation distance, and found that binocular, but not monocular, estimates of the depth between pairs of lights increased with their physical depth up to the maximum depth separation tested, which is 248 meters, indicating that binocular disparity can be scaled for much larger distances than previously realized.
1.1.2. **Optic flow**

Optic flow refers to the distribution of apparent velocities of movement of brightness patterns in an image (Horn & Schunck, 1981). Optic flow often is not treated as a depth cue, nevertheless it provides important depth information which conveyed during the interactions between the target, the observer and the scene. J.J. Gibson first introduced the concept of optic flow, which he termed as ambient optic array, during World War II when he conducted depth perception experiments to help increase the skill of pilots at landing planes. It arises from relative motion of objects and the observer (Gibson, 1950, 1966), and gives information about the three-dimensional structure of the objects (Gibson, 1979). Study shows that infants as young as 8 weeks perceive three-dimensional object shape from optic flow (Arterberry & Yonas, 2000).

When an observer moves forward in the environment, the image on his or her retina expands. The rate of this expansion conveys information about distance from the observer and the object, the observer’s speed and the time to collision. It is commonly assumed that the rate of expansion is estimated from the divergence of the optic flow field. Schrater et al. (2001) found that the rate of expansion could also be estimated from changes in the size (or scale) of image feature, and that pure scale changes could produce motion after-effects. This indicates even though optic flow is such a strong and powerful cue, the integration of other cues can assist and improve the perception of distance, motion and interaction with objects in the environment.

Although a great many studies have shown that binocular disparity is a relatively weak cue compared to optic flow, Palmisano (1996) found that adding stereoscopic cues, or changing size cues to optic flow pattern significantly improves forward linear vection in foveal vision, suggesting both stereoscopic and changing-size cues provide additional motion-in-depth
information that is used in perceiving self-motion and distance.

1.2. Constancy phenomena and illusions

We have reviewed different types of cues to distance perception. In the following sections, we will demonstrate several types of constancies and their related illusions, mainly focusing on constancies under changes of viewing distance. Lightness and color constancy will be briefly discussed in the later section.

1.2.1. Size constancy

![Diagram of size constancy](image)

Figure 2: Demonstration of size perception. When being viewed at a farther distance, object A results in a smaller angular size on the retina compared to that being viewed at a nearer distance (A'). Object B, which has a smaller physical size, results in a same angular size when being viewed nearer.

Veridical perception of an object should be based upon its physical size. According to optical principles, for the same object, the size of the image on the retina changes as the distance from the object to the observer changes. The greater the distance, the smaller the image sensed by the retina is (Figure 2). However, when observing an object under different viewing distances,
the apparent size is similar to the actual physical size of the object. Size constancy is the ability to see an object as the same size, regardless of the change of the retinal image associated with the viewing distance (Gregory, 1963). The phenomenon has been studied extensively not only in human (Boring, 1964; Gregory, 1963; Carlson, 1962), but also in monkeys and other animals (Locke, 1937; Humphrey & Weiskrantz, 1969; Ungerleider et al., 1977; Ewert & Burghagen, 2008). There is also evidence that size constancy is already present in early infancy (Slater et al., 1990). It can be observed under stereoscopic and monocular viewing conditions, e.g., in photographs and drawings (Boring, 1964; Carlson, 1960, 1962; Murgia & Sharkey, 2009).

Under normal viewing conditions, size constancy is nearly perfect with slight overestimation of an object’s size with increasing distance, a phenomenon called over-constancy. A number of studies have the over-constancy phenomenon (Gilinsky, 1955; Carlson, 1960). Gilinsky (1955) did the first experiment to explore the over-constancy. He carried out an outdoor experiment on grassy terrain with all usual cues of distance available. Observers were asked to make judgments of either the objective size or the retinal size of a big white isosceles triangle placed at one of the six distances ranging from 100 to 4000 feet. Both the perceived size and the angular size of the triangle were overestimated. The magnitude of overestimation increased as the distance increased (however, size constancy mechanism breaks down under unusual viewing conditions or exceptionally large distances, at 0.5° visual angle or smaller, Day, Stuart, & Dickinson, 1980). With diminishing depth cues, perceived size of an object drops from the perfect constancy to its angular size. Holway & Boring (1941) tested size constancy under four different conditions: binocular viewing, monocular viewing, monocular with artificial pupil, and monocular with artificial pupil and reduction tunnel. In reduction tunnel condition, a long black reduction tunnel stretching from the observer to the standard stimulus, eliminating most of the
visual frame of reference. Observer matched the size of a comparison disk viewed at a fixed distance to the objective size of a test disk viewed at various distances. Under natural binocular viewing condition, an over-constancy was observed consistent with Gilinsky’s finding. As the depth cues becoming increasingly deprived, the perceived size judgment varied gradually from the objective size to the retinal size. Together with much other evidence, it shows that distance perception is crucial in achieving size constancy.

In addition, many studies (Leibowitz & Moore, 1966; Wallach & Floor, 1971) investigated the effect of accommodation and convergence as cues to distance on size perception. Leibowitz & Moore (1966) found for observation distances up to about one meter, at which accommodation and convergence play a major role as depth cues, perceived size is proportional to the distance. At greater distances, this relationship becomes progressively less marked. They concluded that accommodation and convergence could mediate size constancy only at viewing distances of one meter or less, and that other cues must be operative at greater distances.

Epstein & Broota (1986) showed the effect of attention on whether observers make objective size matches or angular size matches. They presented observers with poster-board squares of various sizes, each covered with a variable array of randomly positioned dots. In one condition, observers were asked to judge the size of the squares presented briefly at various distances. In the other condition, the observers were asked to judge, as quickly as possible, whether the number of the dots on the square was odd or even. After several judgments, they were asked to judge the size of the square seen on the last trial. They found that when attention is directed to the size of the square, they made objective size matches; when attention is directed to the number of the dots on the square, they made angular size matches of the square. These results indicate that size constancy requires attentional allocation to the target.
Mckee & Welch (1992) studied the precision of size constancy. The precision of objective size judgments, made when target disparity changed at random from trial-to-trial, was compared to the precision of angular size judgments made under the same condition. Observers judged incremental changes in the vertical distance separating a pair of horizontal lines. For the objective judgments (in cm), the angle subtended by the target separation decreased with increasing depth consistent with the natural geometry of physical objects. For the angular judgments (in arc min), the angular separation did not change with disparity. For separations subtending an angle < 10 arc min, objective thresholds were considerably higher than angular thresholds, indicating that the precision of size constancy decreased at small scales. At larger scales (20 arc min), the Weber fractions for angular and objective thresholds were nearly equal. They also showed that observers could learn to judge objective size when angular subtense systematically increased with increasing depth in an exact inversion of the natural relationship, although with less precision. The fact that observers could learn this task with little practice suggests that constancy itself may be a learned response.

Explanations.

In order to keep the apparent size of an object invariant with changing viewing distances, an estimate of distance can be used to compensate for the associated changes of retinal size (Boring, 1940; Kilpatrick & Ittelson, 1953; Epstein et al., 1961; Epstein, 1963; Kaufman et al., 2006). It is the so-called size-distance invariance hypothesis (SDIH). Emmert’s law, a phenomenon shows that an afterimage (of necessarily constant visual angle) appears to increase in size when projected to a greater distance. This is a perfect manifestation of SDIH. Many size illusions, such as the Ponzo and Moon illusions, are suggested to be based on this size – distance relationship (Ross, 1967; Dees, 1966; Ross, 2000; Kaufman & Kaufman, 2000).
However, not every researcher agrees with SDIH. For example, Gibson (1966, 1979) explicitly rejected the idea that distance cues are used by the perceptual system in computing or inferring size. He believed that the properties of objects are uniquely represented in the optic array – because the size of an object relative to its surround does not change as viewing distance changes, the nested angles remain in a fixed ratio, and it is directly available once being attended to. Gibson (1966) stated that there is no need to ascribe computation-like process to the brain in explaining why we perceive what we do. This controversy has continued through the past several decades.

Size illusions.

The Ponzo illusion is a manifestation of the phenomenon of size constancy. An object viewed from greater distance subtend a small angular size, but its apparent size remains roughly constant, presumably, because the brain accounts for the angular size variation with viewing distance. And, visa versa, if the object’s angular size does not show the expected variation with viewing distance, the brain infers that its physical size must be varying, resulting in the Ponzo illusion. Leibowitz et al. (1969) tested the object size at varying distances by measuring the magnitude of the Ponzo illusion, and the results showed that the illusory effect was about 45% for three-dimensional actual scenes compared to 30% for two-dimensional photographs of the same scene. It is not surprising that stronger depth cues produced a stronger illusion.

The moon illusion is another illusion in which the moon appears larger near the horizon than it does while above the zenith. As the Ponzo illusion, it is often explained by SDIH (Dees, 1966). When the moon is high above the horizon, the “perceived” distance is beyond the effective limits of the stereopsis cues of distance, and monocular cues are generally absent from
the scene. However, when the moon is viewed at the level of the horizon, the monocular cues of linear perspective, occlusion, etc. are associated with the perceived distance. These cues enhance the accuracy of the distance judgment, thus increase the perceived distance of the moon. Since the angular size of the moon does not change, the mechanism that normally yields size constancy, presumably SDIH, produce a sensation of a larger moon as the perceived distance increases. Perceptually, the assumption of “larger objects are closer” yields the conclusion that the moon is closer over horizon. However, this explanation presupposes an averaging tendency, which is not generally accepted. Some researchers also proposed a relative size hypothesis, but there is no consensus on these explanations, as Ross & Plug (2002) concluded, “No single theory has emerged victorious”. The moon illusion remains a mystery.

1.2.2. Depth constancy

The term ‘distance’ is now commonly used to refer to absolute or egocentric distance whereas the term ‘depth’ or ‘depth interval’ usually refers to relative or stereoscopic depth, and the term ‘depth profile’ refers to the property of the third dimension (in depth) of an object. Stereoscopic depth constancy refers to the ability to accurately judge a depth interval, despite the change in disparity associated with viewing distance. Hans Wallach first raised this issue in 1963 (Wallach & Zuckerman, 1963), where he demonstrated why there should be a stereoscopic depth constancy, just like size constancy:

“It is one of the elementary facts of stereoscopic vision that retinal disparity represents depth quantitatively......Nevertheless, just as the size of a retinal image does not depend alone on the size of the corresponding object, the amount of retinal disparity between two points does not depend exclusively on their distance in depth; in both cases,
the distance of the object from the eyes is important. There should therefore be a
constancy-problem in stereoscopically perceived depth which corresponds to the problem
of size-constancy: if the perceived-depth between two points on an object is to
correspond to the distance in depth between the two points on the physical object, the
distance of the physical object from the eyes must, in some fashion, be taken into account.”

Wallach gave two reasons why disparity should vary with distance: (1) because “disparity
consists in small differences in the width of the retinal images in the two eyes, it must decrease
in proportion to the distance of the object from the eyes as do retinal images themselves”; (2)
because the two eyes view an object from slightly different directions, the greater the viewing
distance, the less the difference in viewing direction, the smaller (in proportion to the viewing
distance) should be the disparity resulted from a given depth interval. He noted that since these
two factors are independent of each other, disparity should decline with the square of the
distance.

Wallach & Zuckerman (1963) showed that manipulation of convergence and
accommodation alone produced a fair degree of size constancy as well as of depth constancy.
Another interesting method of they tried to demonstrate depth constancy involving the use of
anaglyphs. In anaglyphs, the left-eye and the right-eye view of an object or a scene are printed in
different colors, one superimposed on the other. When viewed through colored spectacles, the
right and left eyes see only the corresponding right-eye and left-eye view, thus the anaglyph
produces the stereoscopic effect. They found that when the distance of an anaglyph from the eyes
is changed, stereoscopic depth is altered – increasing this distance enhances perceived depth.
This observation paradoxically illustrates depth constancy phenomenon. Because as viewing
distance increases, the projection of contours in the anaglyphs decreases since its retinal image
decreases. This is consistent with the first reason for the decline of disparity by a square law with distance. The second reason involving the decrease in the projection to the left and right eyes with increasing viewing distance given a depth interval. However, in anaglyphs, it is the projections that are given instead of the fixed depth interval, therefore, these projections remain invariant with distance. Taken together, the disparity caused by anaglyphs varies in proportion to the viewing distance. But the compensating mechanism that normally yields depth constancy must enhance the perceived depth in proportion to the square of the distance, resulting in an increase in the perceived depth in the anaglyphs.

Using a pseudoscope, an instrument that reverses stereoscopic depth, Wallach & Zuckerman (1963) compared the effect of perspective cues on depth with that of oculomotor cues. When viewed through the pseudoscope, observers experienced the expected reversal of depth: the nearer anaglyph – which, due to the pseudoscopic distance cues, appeared to be farther away — showed a greater depth. But when the anaglyphs were placed on a tablecloth, their apparent distances were not reversed any more. Perspective cues override the binocular cues, and objectively more distant object appeared to be farther away, and showed greater depth.

Johnston (1991) did an experiment to test depth constancy for a continuous surface with rich disparity information. She asked observers to judge the shape of a hemicylinder with continuous curved surface presented as random dot stereogram. At a close viewing distance (about 0.5 m), true circular cylinders appeared elongated; at an intermediate distance (about 1 m), perception was close to veridical; at a far distance (about 2 m), cylinders appeared flattened. The author suggested that the observed shape distortion, thus the failure of depth constancy, was a consequence of scaling horizontal disparity with an incorrect estimate of viewing distance.
Glennerster et al. (1996) studied whether subject’s task could affect the judgment of depth. In their study, observers made two types of judgment about the shape of stereoscopically defined surfaces (e.g., amplitude of sine-waves) under identical viewing conditions: one required an estimate of viewing distance for correct performance, the other did not. Depth constancy for the two types of task was about 75% and 100%, respectively. They argued that observers may use a simple “direct” strategy to perform the depth matching task rather than constructing and comparing a metric representation of each surface. Therefore, the extent of depth constancy depends on the task used to measure it.

In a later study, Glennerster et al. (1998) examined the effect of two factors on depth constancy in depth-to-height judgment: 1) the richness of the cues to viewing conditions (reduced or full cue about viewing distance), and 2) the range of stimulus disparities (cylinder depths) presented. Observers judged whether the depth of a stereoscopically presented horizontal hemicylinder was greater or less than its half-height. When used the method of adjustment, they found that depth constancy was reduced for the naive observers in the reduced-cue condition but not for the experienced observers. When used a forced-choice method of constant stimuli to test the effect of the range of stimulus disparities in reduced-cue condition, depth constancy was significantly reduced from “narrow range” to “wide range” condition both in naive and experienced observers. They suggested one possible explanation that, under reduced-cue conditions, the range of stimulus disparities presented was used by the visual system as a cue to viewing distance. Because a given set of objects produced smaller peak-to-trough disparities with increasing viewing distance, conversely, a set of stimuli with large peak-to-trough disparities was most likely to arise from objects at a near viewing distance and vice versa. For the constant stimuli condition, the range of the stimulus disparities observers saw at the
beginning of the experimental run might affect the judgment of viewing distance and hence the perception of shape.

Interestingly, Collett et al. (1991) investigated how angular size and oculomotor cues interact in the perception of size and depth at different distances. In their study, observers looked through a darkened tunnel to see stereoscopically simulated 3D surfaces, thus oculomotor cues were principal cues to distance perception. They found estimates of the magnitude of a constant simulated depth dropped with increasing viewing distance when surfaces were of constant angular size. But with surfaces of constant physical size, estimates were more nearly independent of viewing distance – a demonstration of depth constancy. At any one distance, depth appeared to be greater, the smaller the angular size of the image. With most observers, the influence of angular size on perceived depth grew with increasing viewing distance. Based on these results, they suggested that there are two components to depth scaling. One is related to viewing distance, and the other is related to angular size, and the weighting of the latter growing with viewing distance. They concluded that angular size and viewing distance interact in a similar way to determine perceived size and perceived distance.

Similarly, Bradshaw et al. (1996) studied the effect of display size on disparity scaling from differential perspective (texture gradient) and vergence cues. When differential perspective and vergence angle were manipulated together, approximately 35% of the scaling was required for complete depth constancy. When manipulated separately the relative influence of each cue depended crucially on the size of the visual display. Differential perspective was only effective when the display size was sufficiently large (i.e., greater than 20 deg) whereas the influence of vergence angle, although evident at each display size, was greatest in the smaller displays. For each display size the independent effects of the two cues were approximately additive. Perceived
size (and two-dimensional spacing of elements) was also affected by manipulations of differential perspective and vergence. Their results indicate that both differential perspective and vergence are effective in scaling the perceived two-dimensional size of elements and the perceived depth from horizontal disparities.

Are there any illusions associated with depth constancy? Under normal viewing conditions, up to a distance of 2 m, stereoscopic depth perception compensates well for this decrease in disparity with viewing distance (although there is a study showing that rescaling of the depth signaled by retinal disparity continues at viewing distance far beyond the range at which oculomotor cues are effective (Cormack, 1984)). In other words, perceived depth increases approximately in proportion to the square of viewing distance. Wallach et al. (1979) found when disparities are artificially produced, by anaglyphs or spectacles, or in the context of the Pulfrich effect, they decreased only in proportion to the first power of viewing distance. Depth perception, however, compensates for the normal disparity loss. As a result, there should be a net gain in perceived depth approximately in proportion to the first power of viewing distance. When perceived depth caused by horizontal magnification in one eye or by the Pulfrich effect was measured, it was found to increase approximately in proportion to viewing distance.

In this dissertation, we will focus on studying depth constancy in the context of the StarTrek illusion (Qian & Petrov, 2012). We discovered that depth and the size constancies were related, e.g., the size and depth illusions were strongly correlated across observers. While the illusory size increase of the stimuli could not be canceled by any degree of depth modulation, decreasing the size of the stimuli during optic flow motion canceled or even reversed the illusory depth gradient increase. The results are in support of General Object Constancy model we proposed: besides using the same scaling factor to account for size and disparity variations with
viewing distance, the brain uses the apparent object size to additionally scale depth signals. We will discuss this later in detail.

1.2.3. Contrast constancy

Contrast constancy refers to the ability to perceive objects as having constant contrast independent of size or distance. It was first described by Georgeson & Sullivan (1975). They investigated the contrast perception of high contrast sinusoidal gratings at different spatial frequencies by contrast-matching, and compared the results with contrast sensitivity. They discovered that suprathreshold contrast-matching between different spatial frequencies and between single lines of different widths was performed correctly despite the attenuation by optical and neural factors which cause large differences in contrast sensitivity. Within the limits imposed by threshold and resolution, contrast-matching was largely independent of luminance and position on the retina, indicating a constancy of contrast perception over a wide range of spatial frequencies at suprathreshold. Astigmatic observers showed considerable suprathreshold compensation for their orientation-specific neural deficit in contrast sensitivity. They suggest that spatial frequency channels in the visual cortex are organized to compensate for earlier attenuation, in order to achieve ‘deblurring’ of the image, and to optimize the clarity of vision.

Brady & Field (1995) found that contrast constancy also holds for relatively broad-band patterns – both localized Gabor patches (coherent phase spectra) and bandpass noise patterns (incoherent phase spectra). They also noted that contrast matching is quite accurate as soon as the pattern is suprathreshold, and constancy holds over a wide range of suprathreshold contrasts.

Although Georgeson & Sullivan (1975) did not claim that contrast constancy holds for distance, their demonstration of the relation between apparent contrast and spatial frequency
suggests the existence of such phenomenon, because the spatial frequency of an object varies with viewing distance. Aslin et al. (2004) found that contrast adaptation or contrast gain control is depth dependent. In their study, observers viewed a multiple depth-plane textured surface, in which a small region that varied in contrast adaptation was present only in one depth-plane to produce contrast adaptation. After adaptation, observers performed a contrast-matching task in both the adapted and a non-adapted depth-plane to measure the magnitude and spatial specificity of contrast adaptation. Results indicated that contrast adaptation was depth-dependent under full-cue (disparity, linear perspective, texture gradient) conditions; there was a highly significant change in contrast gain in the depth-plane of adaptation and no significant gain change in the unadapted depth-plane. Under some monocular viewing conditions, a similar change in contrast gain was present in the adapted depth-plane despite the absence of disparity information for depth. Their results demonstrate that mechanisms of contrast adaptation are conditioned by three-dimensional viewing contexts.

Recently, Qian & Petrov (2012) reported a powerful type of contrast and size illusion caused by apparent motion in depth, which, in turn, manifested that contrast perception of an object is invariant with perceived distance. The results suggest that, like size constancy, the brain may use the same scaling factor to account for contrast change with viewing distance. We will discuss the study further in Chapter 2.

1.2.4. Lightness and color constancy

The visual system continually adapts to the intensity/color of the light that illuminates a scene, or the light intensity/color context in which objects exist. As the light in a scene shifts, we usually do not perceive that the objects changes color, but instead adapt to the new context and
interpret object colors accordingly. The ability to perceive the lightness/color of an object as invariant regardless of viewing conditions is called lightness/color constancy.

Although lightness and color constancy has been studied extensively under varying lighting conditions (Adelson, 1999; Rutherford & Brainard, 2002; MacEvoy & Paradiso, 2001; Brainard, 1998; Brainard et al., 1997; Kraft & Brainard, 1999; Gilchrist, 2006), it is also known that the perception of surface lightness is depth dependent (Gilchrist, 1977; Logvinenko & Maloney, 2006; Pereverzeva & Murray, 2009). Schirillo et al. (1990) found that lightness, but not brightness, was influenced by perceived depth geometry. Some researchers used a wide range of manipulation of depth cues (Kitazaki et al., 2008; Landy et al., 1995) to investigate how various combinations of depth cues affect lightness perception in three-dimensional scenes. For example, Kitazaki et al. (2008) found that surface lightness perception was modulated by three-dimensional perception using pictorial, binocular-disparity, and motion-parallax cues additively.

1.3. Summary

We have reviewed distance perception and perceptual constancy phenomena, mainly focusing on size and depth constancy. Distance perception is found to be a crucial process in achieving both of these constancies. Although contrast and lightness constancies are rarely studied under changes of viewing distance, studies have shown lightness or contrast perception are depth dependent, therefore indicating constancy phenomena with respect to distance are universal across various feature dimensions.
Chapter 2: Background

In the previous chapter, we have reviewed several types of constancy phenomena in account of viewing distance. In fact, this ability to compensate the effect of distance is not only found in the visual system but also in other sensory modalities: tactile size constancy was found recently (Jackson & Shaw, 2000; Taylor-Clarke et al., 2004). These phenomena demonstrate one goal: to convey the actual physical dimensions of the world to our perception. Because we have such a prominent ability to recognize the size of an object at various distances, we could be using similar mechanisms for other visual features as well. The contrast constancy phenomenon (Georgeson & Sullivan, 1975) demonstrates that our contrast perception mechanisms compensate for the variation of contrast sensitivity with spatial frequency. Although Georgeson did not explicitly point out the relationship between the perceptions of contrast and depth, its demonstration of the relation between apparent contrast and spatial frequency suggest such a relationship, because spatial frequency varies with distance. Although the contrast constancy has not been profoundly explored the same way as the size constancy, the phenomenon itself gives an example of other aspects of constancy. Indeed, recent studies (Aslin et al., 2004) show that contrast adaptation or contrast gain control is depth dependent.

In our previous study (Qian & Petrov, 2012), we observed a powerful type of contrast and size illusion caused by apparent motion in depth, which we called the StarTrek illusion. We found that an optic flow pattern consists of disks moving in depth strongly modulates their contrast. This phenomenon is interesting not only because it is the first clear demonstration that the percept of depth has a rather strong effect on contrast perception, but it also suggests that the brain applies a regulating rule for contrast variation with viewing distance, the same way as it does for size. Furthermore, we discovered that contrast and size constancies are related, and this
relationship is explained by our General Object Constancy hypothesis.

2.1. StarTrek illusion on contrast

![Figure 3: An example of the stimulus used. The white bars illustrate the radial optic flow created by the moving random disks visible through the circular aperture in the center of the screen.](image)

The StarTrek illusion was induced by a set of high-contrast randomly located disks moving on a gray background (Figure 3). Their motion created an optic flow consistent with the disks being positioned on a fronto-parallel plane moving back and forth with a constant speed, i.e., in a triangle-wave fashion. Disks appearing to move away from the observer grew higher in contrast and larger, while their retinal size and contrast remained constant.
We explored the properties of the StarTrek illusion on contrast: the phenomenon could be observed with as few as 3 – 5 disks. On average, the illusory contrast change was very strong, 25% – 30%, while for some observers the illusion was much stronger. The illusory effect grew even stronger as the motion amplitude increased. The nature and size of the objects creating the optic flow was of little significance: light/dark disks and Difference-of-Gaussian (DoG) disks of various sizes worked equally well. The associated binocular disparity change produced a weaker illusion on its own and contributed little when combined with the optic flow. We suggested this was possibly due to the fact that binocular disparity becomes vanishingly small at distances farther than a few hundreds meters while the optic flow cue is in effect at any distance. On the other hand, the density modulation present in a radial optic flow turned out to be a significant factor of the illusion’s strength, perhaps because radial optic flow is normally associated with the density change of the flowing objects.

We suggested that the StarTrek phenomenon is a contrast-domain counterpart of a size-distance illusion, e.g., the well-known Ponzo illusion. If size constancy is a strategy the brain uses to successfully recognize a certain object at different distances, it is possible that it uses a similar strategy for contrast perception. When an object moves farther away, its image on the retina gets smaller. Due to the pupil having a finite aperture, the retinal image of a disk is increasingly blurred as the disk gets smaller. Consequently, some measure of contrast is lost. Moreover, there is an overall shift of the image content to higher spatial frequencies, where contrast sensitivity of the human visual system is low (Georgeson & Sullivan, 1975). The study suggested that the perception of an object’s contrast remains relatively constant even though our sensitivity to contrast is reduced when viewing objects far away. The same compensating mechanism for the contrast loss with increasing distance applies to all stimuli, even though in our
experimental displays the disks do not reduce contrast during the contraction phase. Because the constancy mechanism boosts the contrast, it produces the StarTrek illusion.

We suggest that the contrast illusion can be affected by how ecologically plausible the optic flow patterns are. We found a stronger illusion when disks appeared to move toward an observer. This might be because, normally, we move forward a lot more than we move backward. Correspondingly, the optic flow in the form of expansion is more common than the optic flow in the form of contraction. Besides, things moving toward us are more ecologically relevant (food, menace, etc.). These two factors cause that the visual system adapts to the changing appearance of objects moving toward us stronger than for objects moving away from us. Consequently, when these expected changes are not observed, we experience greater illusory effects for object moving closer than they moving away.

2.2. Relation between the size and contrast illusions

The size of the disks per se did not significantly affect the illusion strength. However, by adjusting the size of disks progressively during the optic flow motion, the illusory contrast increase could be canceled completely or reversed. Comparing the size and contrast illusions, we found a surprising correlation between the perceived size of an object and its perceived contrast:

(i) The strength of the size illusion was roughly half that of the contrast illusion across observers.

(ii) The relative amounts of size change and contrast change required to null the contrast illusion were about the same for any given observer. Note that this effect of size on the perceived contrast cannot be explained by the finite resolution of the visual system, because we used disks
with angular diameter much larger than that of the Airy disk, and the effect was exactly the same for disks of the two different diameters we used.

(iii) The size change affected the perceived contrast only when objects appeared to move in depth. Simply changing the size of the disks without changing their apparent depth did not result in the perceived contrast change. This point was intuitively clear, but we also ran a control experiment, where observers were required to match the contrast of a disk of varying size to a reference disk of a given constant size and contrast. The control experiment showed that the disk size had no effect on contrast judgments unless the disk diameter was comparable to the Airy disk diameter, which was an order of magnitude smaller than the smallest diameter used in our study.

(iv) The contrast modulation did not affect the size illusion. These results indicated that the apparent size strongly contributes to the apparent contrast, but not vice versa.

2.3. General Object Constancy

We proposed a simple model of size and contrast perception, which explains the above four results. The model suggests a global phenomenon that bridges size constancy and contrast constancy, which we termed General Object Constancy (Figure 4). Our hypothesis is that the brain uses a general object-constancy mechanism that employs a single scaling function for both size constancy and contrast constancy, i.e., scales both retinal size and retinal contrast by the same amount as a function of distance. Additionally, the perceived contrast is scaled by the perceived size change. Because the size and contrast are both scaled as a function of distance, but the perceived size further contributes to scale the perceived contrast and not vice versa, the contrast illusion ends up about twice stronger than the size illusion. The fact that the contrast
illusion can be completely nulled by contrast modulation and size modulation but the size illusion can only be nulled by size modulation is also explained by the model.

![Diagram](image)

Figure 4: General object-constancy mechanism. Brain scales both retinal size and retinal contrast of an object by a factor $k$ as a function of distance. Additionally, the perceived size change contributes to the perceived contrast, which is indicated by the ‘x’ symbol in the diagram.

2.4. Summary

Our previous study have found that the StarTrek illusion is one of the strongest illusions of contrast, which can be explained by the term contrast constancy: normally, objects lose their contrast when viewed from far away, but when this expected loss does not happen, the brain infers that the physical contrast of the object increases as the object moves away. This is perceived as the illusory increase of the object’s contrast. The contrast constancy is largely analogous to the well-known size-constancy phenomenon. In addition, we discovered that size
and contrast, apparently independent features, are directly linked: the contrast illusion nulled by a given amount of contrast change during the optic flow could also be nulled by the same amount of size change; the size illusion could not be nulled by any degree of contrast modulation. This demonstrates that size calculation is done prior to the perceived contrast calculation and the resulting size is taken into account for the contrast calculation. A General Object Constancy model was proposed to unite the well-known size constancy and contrast constancy phenomena: the brain applies a common scaling factor to the object’s size and contrast to compensate for changes in the object’s appearance with viewing distance, and the perceived size affects the contrast perception additionally but not vice versa.

In the following chapters, we will demonstrate the StarTrek illusions on depth, its relation with contrast and size illusions, and how it manifests depth constancy phenomenon in the framework of General Object Constancy.
Chapter 3: General Methods

3.1. Apparatus

The stimuli were displayed on a gray background and viewed through a Wheatstone stereoscope on a pair of linearized 21” ViewSonic G225f monitors (Figure 5). The display resolution was set to 1600x1200 pixels; and for the typical viewing distance of 110 cm, a pixel subtended 1 arcmin.

![Figure 5: Apparatus: Wheatstone stereoscope.](image)

3.2. Stimuli

In this study, the target was a set of high-contrast randomly located pairs of disks moving in a pattern of radial optic flow on a gray background. Peripheral random pairs of disks on a gray background formed a static stencil mask. The mask had a 10° circular aperture positioned in the center of the screen, through which the moving disks could be seen. Their motion created an optic flow consistent with the disks being positioned on a fronto-parallel plane moving back and
forth with constant speed, i.e., in a triangle-wave fashion. The amplitude of the optic flow motion corresponded to the disks moving away to twice the viewing distance. As the disks moved inward new disks filled in along the boundary of the aperture from behind the occluding stencil mask, and moved consistently with the pattern of optic flow. From the point of view of the observer, the density of the disks became higher when they appeared to move away from the observer. Thus we refer to this motion phase as “stimulus contraction” and refer to the motion phase when disks move toward the observer as “stimulus expansion”; the same convention was used in our previous study (Qian & Petrov, 2012).

A disk pair comprised either a small .05° black disk floating in front of a large .15° white disk (Figure 6a), which resembled a pencil viewed head-on; or a white .05° disk floating upper left to a dark disk of the same size but softer edges Figure 6b, which resembled a white disk casting a shadow. From now on, we call the stimuli shown in Figure 6a the ‘pencil’ stimuli and that shown in Figure 6b the ‘shadowed disk’ stimuli. Binocular disparity was added between the paired disks to create 3D percepts of a ‘pencil’ and a ‘shadowed disk’, respectively. The two types of stimuli were tested in separate experimental blocks. 100 pairs of disks were displayed in each trial, which lasted for 2 seconds and included one contraction-expansion motion cycle of the optic flow. Observers carried out two experimental blocks for each condition, 150 trials for each block.

3.3. Subjects

Thirty-two observers with normal or corrected visual acuity were tested. Twenty-nine of the observers were naive to the purpose of the study; only three were experienced psychophysical observers. Observers were trained for a short time (2 - 5 min) to get acquainted
Figure 6: Stimulus: a. small black disks floating in front of large white disks (pencil tips viewed head-on); b. white disks floating upper left to dark disks of the same size (disks casting shadows). Pairs of disks moved across the screen in a pattern of radial optic flow. The amplitude of the optic flow motion corresponded to the disks moving away to twice the viewing distance with the stimuli and the task.
3.4. Psychometric Procedure

Figure 7: Experimental procedures. “Shadowed disk” stimuli as examples.

Observers were indicating whether the depth profile of a disk pair was changing in the course of the optic flow by clicking left and right mouse buttons. For example, for the ‘pencil’ stimuli, observers were asked to press the right mouse button if they perceived the ‘pencil’ tip getting sharper while the disks were moving to the center of the screen (contraction phase). For the ‘shadowed disk’ stimuli, they were asked to press the right mouse button if they perceived the depth separation between the disk and its shadow increasing during the contraction phase. Sometimes, we used the ‘taking off’ or ‘landing’ analogy to help the participants to understand the task: “the white disk is a spacecraft taking off/landing on the planet, the black disk is its
shadow”. The depth illusion was measured with a nulling paradigm, where the relative disparity for each pair varied in such a way as to stabilize the depth profile in the course of the optic flow. In other words, to null the illusory effect, a gradual disparity decrement or increment was applied to all the moving disks as they moved away and an equal gradual increment or decrement was applied as they returned. We found that the disparity modulation given by the following formula produced a fairly constant depth-change percept in the course of the optic flow and was suitable for the nulling paradigm:

\[ D(d) = \frac{D(d_0)}{1 + \frac{A \Delta d}{d_0}} \]

where \( d_0 \) stands for the actual viewing distance, \( \Delta d = d - d_0 \) stands for the modulation of the distance from the observer, \( d \), as simulated by the optic flow, and \( D(d_0) \) stands for the relative disparity between the pairs of disks for \( d = d_0 \). The nulling amplitude of the disparity modulation, \( A \), was calculated by a modified version of the Bayesian adaptive algorithm, devised by Kontsevich & Tyler (1999). The same formula was used in the previous study (Qian & Petrov, 2012) to describe the modulation of size and contrast, when measuring the size or the contrast illusions. Note that because \( A \) was always positive, disparity always decreased as the simulated distance \( d \) increased. For example, when \( A = 0.5 \) and \( d = 2d_0 \), \( D(d) = \frac{D(d_0)}{1 + 0.5} = 0.67D(d_0) \). The illusion strength was measured as the percent change of \( D \) necessary to null the illusion for the maximum distance, \( d = 2d_0 \).

Observers carried out two blocks of 150 trials per block for each condition. Uncertainties for the measurement of \( \Delta D \) were taken as the maximum of the two: (i) variation of the \( \Delta D \) estimate calculated from the results of the adaptive algorithm, (ii) variation of the \( \Delta D \) estimates
in between the two experimental blocks. The resulting uncertainties (one SEM) are represented by error bars in the figures.
Chapter 4: Illusion of Depth Gradient

4.1. Introduction

In the Chapter 2, we have reviewed our previous study on StarTrek illusion in contrast perception domain. Our results showed that the contrast constancy and size constancy are related, and proposed a General Object Constancy model which suggests that the brain uses the same scaling factor to account for the size and contrast change with viewing distance. Besides contrast, an object’s size and shape, including its profile in depth, are likely to be perceived as invariant across changes of viewing distance.

Size constancy, which usually refers to the two-dimensional shape of an object, has been studied extensively, and theories, such as SDIH, have been proposed to explain the size constancy phenomenon (see Chapter 1 for details). Real objects are also observed in the third dimension, which defines their depth profile. Although stereoscopic depth constancy was demonstrated a long time ago (Wallach & Zuckerman, 1963), unlike size constancy which attracted a great deal of attention, relatively few studies on depth constancy can be found. Depth profile, as encoded by various depth cues on the retina, changes with viewing distance. In particular, this may result from binocular disparity changing approximately as the inverse of the square of the viewing distance (Wallach & Zuckerman, 1963; Foley, 1980, 1987; Richards, 1985). Hence, to calculate the true depth profile of an object based on its disparity profile, the brain must estimate the viewing distance and scale the disparities accordingly (Ono & Comerford, 1977; Glennerster et al., 1996). Even if the depth profile is determined up to a constant affine transformation (Petrov & Glennerster, 2004, 2006), the affine profile needs to be corrected according to the viewing distance. Because viewing distance was physically varied
when studying constancy phenomena, depth cues like convergence, accommodation, texture gradients, familiar size (e.g., monitors), or others could be used by the visual system to adjust the depth profile percept in accordance with viewing distance. We show here that depth constancy occurs even if the depth cue used is non-stereoscopic, and there is no physical change in viewing distance. All that matters is a perceived change in viewing distance evoked by any depth cue. Here we used radial optic flow as such a cue.

We report new illusions of depth induced by optic flow, much stronger than the accompanying size and contrast illusions we had measured previously (Qian & Petrov, 2012). The correlation we discovered between size constancy, contrast constancy, and depth constancy which was studied here within the same paradigm suggest that the brain uses a similar stabilization mechanism to account for effects of viewing distance on various object features, in support of the General Object Constancy proposed in Qian & Petrov (2012).

![Figure 8: Demonstration of the depth gradient illusion during the contraction phase.](image)

In Experiment 1–4, we tested the ‘pencil’ stimuli shown in Figure 6a. Twenty-four observers participated in the experiment. All observers reported that the pencils appeared to grow
sharper and larger in diameter during the contraction phase and that the reverse happened during
the expansion phase (see Figure 8). The perceived change in the pencil’s diameter could be
explained by the size illusion; the perceived sharpness increase revealed a new illusion of depth.
We termed this illusion the depth gradient illusion as the pencil’s sharpness represents the depth
gradient.

4.2. Experiment 1: Depth gradient illusion.

In Experiment 1, we tested the strength of the depth gradient illusion. The depth gradient
illusion was accompanied by the size illusion, which replicated our previous findings for the size
illusion induced by the optic flow. Importantly, the illusion of depth had to be stronger than the
size illusion, because the rate of illusory depth change had to exceed the rate of the illusory size
change in order for the perceived sharpness to increase. In other words, if both illusions were of
the same magnitude, the perceived pencil sharpness would have been constant, only the pencil’s
overall scale would have varied.

Methods.

Four observers participated in this experiment. They were instructed to judge whether the
perceived sharpness of the pencil increased during the contraction phase. The apparatus shown in
Figure 5 and the disparity nulling paradigm were used (for details see the General Methods
chapter).

Results.

Figure 9a shows the disparity decrease required to null the illusory sharpness increase of
the pencil for the four observers. Figure 9b shows the observer average for the depth gradient
Figure 9: Depth gradient illusion. (a) Top: The dark blue bars show the disparity decrease required to null the illusory sharpness (depth gradient) increase for individual observers. (b) Bottom: Comparison between the averaged nulling value (disparity change) for three types of illusion. The blue bar indicates the average illusory sharpness increase. The green bar and the orange bar show the average illusory contrast increase and the size increase from the previous study (Qian & Petrov, 2012).

The blue bar indicates the average illusory sharpness increase. The green bar and the orange bar show the average illusory contrast increase and the size increase from the previous study (Qian & Petrov, 2012).
for the latter two illusions were taken from our previous study (Qian & Petrov, 2012). The amount of nulling for the depth gradient illusion was the greatest: on average, it was about 43%, compared to 30% for the contrast illusion and 15% for the size illusion, \( F(2, 14) = 23.28, p < 0.005 \).

This is quite surprising, considering that the size illusion is perceptually prominent yet only yields about 15% size variation. The depth gradient illusion is perceptually more subtle compared to the size illusion, however, it is much more stronger given the nulling values. Note that both the size illusion and the depth gradient illusion used the same StarTrek paradigm. Even though there are minor changes to the stimuli, the experimental procedures and the nulling methods are essentially the same. Therefore, this significant difference observed here could only be due to the differences in the mechanisms of the size and the depth perception. Taking into account that the depth illusion and the size illusion were opposing each other in the depth gradient illusion, one might conclude that the depth illusion per se is much stronger than the size illusion. This speculation is in accord with the fact that disparity falls off approximately as the square of the viewing distance (Wallach & Zuckerman, 1963), while size falls off as a linear function of the viewing distance.

4.3. Experiment 2: Effect of object’s size on the depth gradient illusion.

Since the size illusion is a confounding factor in the depth gradient illusion, we wanted to measure the magnitude of the depth gradient illusion without the illusory size change, i.e., keeping the perceived size constant during the optic flow. To this end, we first measured the size illusion for each observer using the ‘pencil’ stimulus, then used the obtained nulling value to cancel the size illusion for each observer and measured the depth gradient illusion.
Methods.

In order to measure the size illusion, the relative disparity between the white and black disks was set to 0 to avoid any possible distraction from the depth percept of the ‘pencil’. In this case, the white and black disks in a pair appeared to be flat concentric circles. The same four observers as in Experiment 1 participated. They were instructed to judge whether the perceived size of the disks appear to be larger or smaller during the contraction phase. The size nulling paradigm was the same as in our previous study, given by formula (2) (Qian & Petrov, 2012). To measure the depth gradient illusion while keeping the perceived size constant, the relative disparity between the disks was re-introduced, and the size illusion for the pencil stimulus was canceled by modulating the diameter of the black and white disks given the nulling values. The task remained the same as in Experiment 1, the same four observers were asked to judge the sharpness change.

Results.

The results are shown in Figure 10 with black dots. There was a strong correlation between the illusory size increase and the illusory sharpness increase. Those observers who perceived a strong size illusion also perceived a strong depth gradient illusion, and vice versa. This was similar to our previous study, where we observed a strong correlation between size and contrast illusions across observers. On average, the relative decrease of the disk size required to null the size illusion was about half of the disparity decrease required to null the depth gradient illusion. For example, one observer experienced an 11% illusory size variation and a 21% illusory sharpness variation.
Figure 10: Comparison between the illusory size (x-axis) and depth gradient (y-axis) change of the pencil, measured by adaptively varying the disk size and the relative disparity between the disks respectively. Each datum represents a different observer. Data from Experiment 2 are shown in black and data from Experiment 1 are shown in red. The black and red curves show parameter-free predictions of the General Object Constancy model, $y + 1 = (x + 1)^2$ and $y + 1 = (x + 1)^3$ respectively (see Appendix A).

Data from Experiment 1 is shown in Figure 10 with red dots for comparison. Since the same four observers participated in these two experiments, their data from Experiment 1 were correlated with their size illusions the same way as for Experiment 2. Strikingly, for all observers, the depth gradient illusion was weaker in Experiment 2 than in Experiment 1. This is counterintuitive because in Experiment 2, the diameter of the pencils was decreasing during the contraction phase, which in turn, was increasing their disparity gradient. The physical diameter of the pencils was constant in Experiment 1, hence, a stronger depth gradient illusion would be expected in Experiment 2 than in Experiment 1. At a first glance, this result seems to be paradoxical, but it can be easily explained by the General Object Constancy model we proposed,
as will be discussed later. The black and red curves show parameter-free predictions of the General Object Constancy model (see Appendix A for details). The black curve fits the data very well. The red curve provides a prediction of where the data should lie, given that the data have large error bars. Even though quantitatively, it does not fit the data well, the model qualitatively predicts the change (from black to red data) in the right direction, which is totally counterintuitive. Based on common sense, one would expect the black curve to be above the red curve, while the model and the data show the opposite.

Taken together, our model gives reasonable predictions to six out of eight data points. The reason for the poor model prediction in Experiment 1 might be that the model does not operate well in highly unrealistic situations. Because the perceived size of the ‘pencil’ is expanding during the contraction phase, and vice versa during the expansion phase, perception contradicts our expectation under normal viewing conditions. It is more difficult and less reliable to make the depth judgments, since it is hard to interpret the stimuli in a reasonable way. Compared with the stimuli used in Experiment 2, the perceived size remained constant, so the stimuli resembled what they should look like in real life. The depth judgments are more accurate in this case, indicated by the smaller error bars. However, further experiments are needed to test this point.

4.4. Experiment 3: Effect of disparity nulling on the size illusion.

Experiment 2 showed that size perception affects the magnitude of the depth gradient illusion in a paradoxical fashion. In this experiment, we wanted to test whether, conversely, disparity manipulations affect the size illusion.
Methods.

For this purpose, we used the same pencil stimulus, but instead of judging the sharpness, the observers were asked to judge whether the diameter of the pencils increased or decreased during the contraction phase. As in Experiment 1, disparity between the white and black disks was modulated adaptively, but now in an attempt to null the size illusion. Eight observers participated in this experiment.

Results.

For seven out of eight observers, the size illusion could not be nulled by disparity manipulations no matter how large the changes were. For the remaining observer, the disparity manipulation did null the size illusion, but the required disparity change was quite high, 49%. We have no satisfactory explanation for the result from this observer, since he has normal vision and was quite confident with his judgment.

Except for this particular observer, we have found that the disparity modulations, which result in variations in sharpness of the pencils, did not affect the size perception of the pencils. This is similar to our previous study (Qian & Petrov, 2012), where we found that manipulating the perceived size could affect the contrast perception, while the contrast modulations did not influence the size perception.

4.5. Experiment 4: Adding global motion in depth.

In all the experiments described thus far we used optic flow to create the percept of a viewing distance change. Normally, such optic flow would be accompanied by the corresponding global disparity change. Therefore, in this experiment we tested whether the depth gradient
illusion can be made stronger by adding such global disparity modulation to all disks, consistent with the disks moving back and forth in depth. In our previous study (Qian & Petrov, 2012), the same manipulation applied to the size and the contrast illusion made no difference, and one might expect that this would also hold true for the depth gradient illusion.

![Graph showing the illusory increase in depth gradient with added global disparity.](image)

**Figure 11:** The illusory increase in depth gradient with added global disparity
modulation. (a) Top: Blue bars show the disparity decrease required to null the illusory sharpness increase for each observer. (b) Bottom: Comparison between the average strength of the illusion with and without global disparity, shown by the pink and blue bars respectively.

Methods.

The same ‘pencil’ stimulus was used, except for the addition of the global disparity modulation consistent with the optic flow. Disparity nulling was used. Eleven observers participated in this experiment.

Results.

When optic flow is the only cue to depth, we experience an increase of the perceived distance of the disks (to 2 x 110cm ideally) even though the physical viewing distance does not change. When the global disparity is added in accordance with the optic flow, the percept of motion in depth becomes visibly stronger. Figure 11a shows the individual data and 11b shows a comparison between the ‘local disparity ’ condition, where only the relative disparity between the disk and its shadow was applied, and the ‘global disparity’ condition, where the global disparity was applied in addition to the local. The average strength of the illusion was about 38%. Despite a great amount of variation between observers, most of them observed an illusory sharpness variation between 30% and 50%. Adding global disparity did not affect the strength of the depth gradient illusion significantly (t(13) = 1.29, p > 0.1, Figure 11). This result indicates that optic flow alone is a strong enough depth cue to render the additional global binocular disparity cue insignificant.

This is consistent with Wallach & Zuckerman (1963) study where they used a
pseudo-scope to reverse stereoscopic depth, but this manipulation failed when a plaid tablecloth was provided in the scene. Similarly, O’leary & Wallach (1980) showed that linear perspective cues for distance prevailed over the conflicting binocular cues when judging the slant of the target plane, which even resulted in the subjective perception contradicting the objective target position. By creating cue conflicts between the linear perspective and oculomotor cues, such as accommodation and convergence, they separated the effect of these two cues and concluded that the linear perspective cue was a stronger cue to depth. If the linear perspective cues induced by the plaid tablecloth could override the conflicting binocular disparity cues, optic flow cues in principle provide an even stronger depth cue than perspective cue therefore could overwhelm the binocular disparity cues.


Instead of keeping the size of the pencil constant, as in Experiment 2, we wanted to test whether modulating the scale of the pencil could affect the depth gradient illusion. Specifically, to decrease the two-dimensional size as well as its disparity profile in such a way that the pencil shrinks in three-dimensional size (scales down uniformly) as it moves in depth but preserves its shape. In this way, we could directly measure the effect of the size/scale modulation on the depth gradient illusion.

Methods.

The purpose of this experiment was to test whether uniformly scaling down the pencil could cancel the illusory sharpness change, so the same formula (see Page 41, General Methods chapter) was applied to both size and disparity. In the formula, parameter A was calculated by the adaptive algorithm, and this A was applied to both size and disparity (note that we did not
expect to cancel the size and depth gradient illusion at the same time using this formula. As long as the depth gradient illusion was cancelled, the size of the pencils could appear to be larger or smaller. Four observers participated in this experiment. The task remained the same as in Experiment 1, 2, and 4.

Figure 12: The effect scale on the depth gradient illusion. (a) Top: The dark blue bars show the

![Bar chart showing nulling value for depth gradient illusion.](image)

![Bar chart showing averaged nulling value.](image)
scale decrease required to null the illusory sharpness increase for individual observer. (b) Bottom: Comparison of the averaged nulling value between the scale nulling and the disparity nulling. The blue and yellow bars indicate the scale nulling and disparity nulling respectively.

Results.

Figure 12a shows the scale decrease required to null the depth gradient illusion of the pencil for the individual observer. Figure 12b shows a comparison between the average data between scale nulling and disparity nulling, given by the blue and the yellow bars respectively. The average nulling value of scale is about 16%, and is significantly lower than the nulling value of disparity, \( t(6) = 7.24, p < 0.001 \). One of the observers also participated in Experiment 1 and 2, the size illusion was 13%, and the depth gradient illusion measured in Experiment 1, 2, and 5 were 43%, 21% and 14% respectively. The reduction in nulling value indicates that perceived size can effectively modulate depth perception as long as it covaries with disparity (i.e., size and disparity were modulated together in the same direction). Note that the size illusion and the depth gradient illusion measured in this experiment are almost the same for this observer, which means that the size illusion was canceled in this experiment. The size illusion was also cancelled in Experiment 2, but then cancellation required much more disparity modulation than in Experiment 5 when disparity and size covaried. Based on these results, one might speculate that manipulating perceived size could dominate the disparity signals, however, we do not have enough data to validate this speculation.

On the other hand, even though the scale of the pencil does not come directly into the disparity gradient calculation, the visual system expects the pencil size change and the disparity
gradient change to be correlated, as it naturally happens when an object is moving in depth. This is similar to our recent finding, where the analogous size manipulation was shown to strongly affect the perceived contrast of an object even though the objects size does not come into the contrast calculation in a trivial fashion (Qian & Petrov, 2012).

4.7. Discussion

The StarTrek illusion (Qian & Petrov, 2012) was used to explore the phenomenon of depth constancy in the current study. Using the ‘pencil’ stimulus, we demonstrated a new illusion of the depth gradient, where the gradient was perceived to vary during the optic flow. This was an even stronger illusion, 43% illusory variation on average, compared to the contrast illusion, 30%, and the size illusion, 15%, reported in our previous study (Qian & Petrov, 2012). Experiment 2 showed that the strengths of the depth and size illusions were correlated across observers and revealed a paradoxical effect of perceived size on the depth gradient illusion, wherein smaller sizes corresponding to larger disparity gradients produced weaker depth gradient percepts. No such effect was observed in the opposite direction, from depth to size, in Experiment 3. Experiment 5 showed that manipulating the scale of the pencil could also null the depth gradient illusion, and the required nulling value significantly reduced compared to that of Experiment 1 and 2. Experiment 4 showed that adding binocular disparity that varied in accordance with the optic flow motion did not enhance the illusion. This is consistent with the results of a similar manipulation in our previous study, and several other studies (Wallach & Zuckerman, 1963; O’leary & Wallach, 1980) which used linear perspective cues instead of optic flow.

The depth illusion we observed might result from a depth constancy mechanism
implemented in the brain. Under normal viewing conditions, when viewing distance increases, an object’s depth profile (encoded by the binocular disparity) decreases. Nevertheless we do not see the object’s depth profile getting flatter, it is relatively invariant to viewing distance change. We hypothesize that depth constancy may be implemented similarly to size constancy via scaling the binocular disparity by a function of viewing distance. Given that our optic flow stimulus created a strong percept of viewing distance change, this scaling transformation was applied to the (constant) disparity signal in the stimulus. As a result, the depth illusion was observed, such that the perceived depth gradient increased in the contraction phase and decreased in the expansion phase.

In Experiment 1, where the size illusion was observed along with the depth illusion, the illusory depth gradient increase was significantly stronger than in Experiment 2, where the size illusion was nulled. At the first glance, this appears paradoxical, because increasing size (pencil diameter) decreases the depth gradient, and, hence, should weaken the depth gradient illusion. In our previous study, we investigated contrast and size illusions in the same optic flow paradigm. In particular, we discovered that in order to explain the contrast illusion, another scaling factor, in addition to viewing distance, was required. This factor was proportional to the perceived size change in the course of optic flow and significantly increased the contrast illusion compared to the size illusion. Although counterintuitive, the paradoxical effect of the object’s size on its perceived depth profile revealed by Experiments 1 and 2, is explained by the same size factor scaling the perceived depth gradient (see Appendix A for more details).

In order to account for the depth gradient illusion, we supplemented the General Object Constancy Model proposed in our previous study (Qian & Petrov, 2012) with depth as a new feature (Figure 13). The model posits that the brain uses the same scaling factor for size,
contrast, and depth profile, i.e., it scales retinal size, retinal contrast, and retinal disparity by a factor $k(d)$, which is a function of viewing distance $d$. Because, unlike size, disparity decreases as the square of $d$, the factor $k$ is squared in this case to ensure a constant depth percept. This factor alone makes the depth illusion much stronger than the size illusion. In addition, the change in perceived size contributes another factor $k'$, which scales both the perceived contrast and depth profile ($k'$ is squared in the latter case). To obtain depth gradient, the depth profile signal is divided by the perceived size. Because of $k'$, the depth illusion is significantly stronger in Experiment 1, where the perceived size increased during the contraction phase, than in Experiment 2, where the perceived size was constant. The model provides parameter-free predictions to the results of Experiments 1 and 2 shown with the red and black curves in Figure 10 and given by $y + 1 = (x + 1)^3$ and $y + 1 = (x + 1)^2$ relationships respectively.

Mathematical details are discussed in Appendix A. The model also explains the results of Experiment 3, since, analogous to the contrast illusion in our previous study, the perceived depth does not factor into the perceived size calculation.

As discussed in Chapter 1, Wallach & Zuckerman (1963) noted in their article that the two factors that lead to the square law of disparity varying with distance are “the small differences in the width of the retinal images in the two eyes” and viewing “an object from slightly different directions” by the two eyes. Other studies have confirmed that size perception does contribute to depth perception, although some stressed the angular size of an object (Collett et al., 1991), others stressed the perceived size (Bradshaw et al., 1996). Our model is in support of the statement that the perceived size affects depth perception. In addition, the model is in accordance with a proposed neural mechanism of depth constancy (Bishop, 1994), suggesting that size and depth constancies are regarded as the first and second stages of a linked two-stage
process. We will discuss these findings and theories in Chapter 6.

Figure 13: General Object Constancy mechanism. The brain scales disparity, retinal size and retinal contrast by a factor \(k\) as a function of distance. Additionally, the perceived size change contributes another factor, \(k'\), to the perceived contrast and the perceived depth. Both factors contribute to the depth perception squared to ensure depth constancy. To obtain depth gradient, the depth profile signal is divided by the perceived size.

Our model suggests that perceived size, depth and contrast all depend on a viewing distance estimate. There are neurophysiological evidences showing that size perception is modulated by both feedforward signals originating from retina to primary visual cortex and feedback from higher visual areas, providing the viewing distance information. Murray et al. (2006) found that three-dimensional contextual information could lead to size illusions reflected in the spatial pattern of activity in V1. However, how can complex three-dimensional contextual information influence the spread of activity pattern in V1? A possible explanation is through
feedback from higher visual areas. Indeed, Fang et al. (2008) studied whether changes in the spatial distribution of activity in V1 depend on the focus of attention, which would suggest feedback of contextual information from higher visual areas. Similar to Murray’s study, they presented two identical rings at close and far apparent depths in a three-dimensional scene to induce a size illusion. Using functional magnetic resonance imaging, they replicated Murray’s results, that the spatial distribution of V1 activity induced by the far ring was shifted toward a more eccentric representation of the visual field, and vice versa, consistent with their perceptual appearances. This effect was significantly reduced when the focus of spatial attention was narrowed with a demanding central fixation task. They reasoned that focusing attention on the fixation task resulted in reduced activity in – and therefore reduced feedback from – higher visual areas that process the depth cues. Moreover, in an event-related potential study (Liu et al., 2009), observers viewed a sphere of a fixed angular size positioned at either a far or close position within a 3D virtual scene, or at either an upper or lower screen position on a plain gray background. The visual-evoked potentials were recorded while observers fixating on and attend to the sphere. The results showed that the amplitude of visual P2 component was affected by sphere position in the three-dimensional scene condition only, suggesting that the activity level of the primary visual cortex was modulated by the size illusion at later stages of visual processing.

Not only size perception, single cell recordings (Trotter et al., 1992, 1996, 2004) have demonstrated gain-modulated disparity tuning cells in V1, V2, and MT, whose firing rates depend on viewing distance. In particular, Trotter et al. (1992) found that the responses of a large majority of neurons in V1 were modulated by the viewing distance in alert, behaving monkeys. This phenomenon affected particularly disparity-related activity and background activity and was
not dependent on the pattern of retinal stimulation. Therefore, they concluded that extra-retinal factors, probably related to vergence or accommodation, or both, could affect processing early in the visual pathway, and such modulations could be useful for judging viewing distance, and scaling retinal disparity to give information about three-dimensional shape. Furthermore, Trotter et al. (2004) investigated the neural mechanisms underlying visual localization in 3D space in area V1 of behaving monkeys. Interactions between retinal disparity and viewing distance have been shown in foveal V1; they have observed a strong modulation of the spontaneous activity and of the visual response of most V1 cells that was highly correlated with the vergence angle. These gain effects suggested that neural horizontal disparity coding was favored or refined for particular distances of fixation. At these large retinal eccentricities they found that vertical disparity is also encoded with tuning profiles similar to those of horizontal disparity coding. In support of our model, these findings imply that the perceived size and the perceived depth calculations depend on viewing distance information through feedback from higher visual areas. See Chapter 6 for more discussion.

4.8. Conclusions

The StarTrek illusion demonstrates several strong illusions across different feature dimensions, which reveals intriguing new phenomena. Size and contrast illusions were studied in our previous work, where we correlated the illusions across observers and discovered specific relationships between the two. In a similar fashion, the size and depth gradient illusions induced by optic flow were investigated in this study.

Our results demonstrate that perceptions of size, depth gradient, and contrast, apparently
independent visual features, are interconnected in a nontrivial fashion: 1) in our previous study, we found that the contrast illusion nulled by a given amount of contrast change during the optic flow could also be nulled by the same amount of size change but not vice versa; 2) similarly, in the current study, we found that the depth gradient illusion nulled by disparity change could also be nulled by scale, and manipulating the perceived size could affect the depth gradient illusion but not vice versa. All three features are calculated from the corresponding retinal measures scaled by a common function of viewing distance. In addition, the perceived size of an object scales retinal contrast and depth signals, presumably by a similar function of viewing distance, sometimes producing paradoxical effects. Taken together, these results support the General Object Constancy model uniting the size constancy, stereoscopic depth constancy and contrast constancy phenomena into a single framework.
Chapter 5: Illusion of Depth Separation

5.1. Introduction

In the previous chapter, we have studied a new illusion of depth gradient and its effect on the size illusion using the ‘pencil’ stimulus. We found that these two illusions were strongly correlated across observers, and the correlation could be explained by the General Object Constancy model proposed in Qian & Petrov (2012). By uniting size and depth constancies, the model demonstrates how the depth-profile of a pencil is preserved when viewing distance was changing. However, the depth gradient illusion emphasizes the shape of an object rather than ‘depth’ per se, and the strength of the illusion is influenced by both the depth interval between the disks that formed the ‘pencil’, and the size of the ‘pencil’, i.e., the diameter of the white and the black disks. In this chapter, we employed another type of stimulus to further study the phenomenon of depth constancy and its relation with size constancy. The ‘shadowed disk’ stimulus shown in Figure 6b was used in Experiment 6 – 9 for this purpose.

Twenty-six observers participated in these experiments. During the contraction phase, observers reported that both the horizontal and depth separation between the white and black disks within a pair appeared to be increasing; and vice versa for the expansion phase. The illusory increases in the perceived horizontal and depth separations between the white and black disks may be attributed to the size and depth illusions respectively. However, unlike the depth gradient illusion, we can minimize the contribution of the size illusion by asking the observers to judge the depth separation only. The illusory change of the depth profile here is termed the depth separation illusion. Since the black disks almost always were perceived as the shadows of the white disks (Figure 14), from now on, we refer to the black disk as the shadow for convenience.
However, the effect of the size illusion could not be completely eliminated, as we will show in the following experiments.

![Figure 14: Demonstration of the depth separation illusion during the contraction phase.](image)

5.2. **Experiment 6: Depth separation illusion.**

In this experiment, we tested the strength of the depth separation illusion. Unlike the previous experiments, wherein the size illusion ‘opposed’ the depth illusion, here the size illusion ‘assisted’ the depth illusion. (Recall that the angular separation positively covaries with the depth separation under normal viewing conditions, so the resulting compensation provides the assist.) Thus, we expected to observe a stronger illusory increase of depth separation.

**Methods.**

Ten observers participated in the experiment. They were instructed to press the right mouse button if they perceived the depth separation between the white disks and their shadows increasing during the contraction phase. In order to minimize the possible influence of the size
illusion, we stressed the depth separation instead of the “separation”, and the ‘taking off’ or ‘landing’ analogy was sometimes used to help the observers to better understand the task. For instance, we asked them to imagine a spacecraft ‘taking off’ or ‘landing’ scenario: “the white disk is a spacecraft taking off/landing on the planet, the black disk is its shadow”. About 1/3 of the observers were told this analogy. The same apparatus and the nulling paradigm were used as in the previous experiments (for details see the General Methods chapter).

Figure 15: Comparison between the averaged nulling value for the depth separation and depth gradient illusion. On average the illusory depth increase was 47%.

Results.

Figure 15 shows a comparison between the depth separation and the depth gradient illusion. Despite of the small individual differences between the observers, the illusory depth variation was phenomenally high for each observer without exception. All had observed 40% – 50% illusory change in depth separation between the disks and their shadows. Because the size
illusion no longer opposed the depth illusion, as the case for the depth gradient illusion, but enhanced the depth illusion, we expect that the illusory effect for the depth separation would be stronger than that for the depth gradient. Indeed, we found, on average, the illusion of depth separation was 47% compared to 43% in Experiment 1 ($t(12) = 3.95, p < 0.005$).

Figure 16: Demonstration of the depth illusion calculation. The solid white and black disks show the actual position of one pair of the disks from the top view. The semi-transparent white and black disks show their illusory positions by the end of a contraction phase. The depth illusion indicated by the question mark is 28%.

We can calculate the ‘veridical’ depth illusion (indicated by a yellow question mark in Figure 16), i.e., without the effect of the size illusion, based on the results of the depth separation illusion. One pair of the disk and its shadow (solid white and black disks) is shown from the top view. $x$ indicates their horizontal separation, and $y$ indicates their separation in depth. The semi-transparent disks show the illusory position by the end of a contraction phase. 15% corresponds to the illusory angular separation change (size illusion) and 47% corresponds to the depth...
separation illusion. The dashed line is parallel to the top slanted line, hence, the segment indicated by the question mark is the ‘left-over’ illusory depth separation eliminating the contribution of the size illusion. According to the geometry,

$$\tan \alpha' = \frac{y(1 + 0.47)}{x(1 + 0.15)} = 1.28\tan \alpha$$

we obtain that the depth illusion which purely attributes to the viewing distance change is 28%. Compared to the results of Experiment 2 in the previous chapter, where the depth gradient illusion was measured while keeping the perceived size constant, and was essentially equal to the veridical depth illusion calculated here, the depth illusion was about 30%. The small difference between the calculation and the result from Experiment 2 could be due to random errors because of individual differences. These results indicated that the two illusions, although employed different stimuli and addressed to different depth profiles, were robust under various conditions and may well be related to each other, although further work would be needed to demonstrate this.

5.3. Experiment 7: Adding global motion in depth.

Similar to Experiment 3, we tested whether the depth separation illusion can be further enhanced by adding global disparity modulation to all disks consistent with the disks moving back and forth in depth.

Methods.

The same stimulus as in the Experiment 6 was used here except that the additional binocular disparity modulation consistent with the viewing distance modulation, as conveyed by
the optic flow, was applied globally to all moving disks. Seven observers participated in the experiment and were tested on both conditions in separate blocks. Other experimental procedures remained the same as in the previous experiments.

Results.

Figure 17 shows a comparison between the ‘local disparity’ and the ‘global disparity’ conditions. On average, the depth separation illusion was about 47%. The added global disparity cue did not affect the strength of the depth separation illusion significantly ($F (1, 27) = 0.32, p > 0.5$). This result is consistent with our previous study and Experiment 3: optic flow by itself is a strong enough depth cue to make the additional global binocular disparity cue of little significance.

Figure 17: Comparison between the averaged nulling value for the ‘local disparity’ and ‘global disparity’ conditions. Observers were tested by both conditions in separate experimental blocks.
5.4. Experiment 8: Disparity nulling vs. angular separation nulling.

Similar to Experiment 2, where we studied the effect of the size perception on the depth gradient illusion, here we wanted to test whether modulating the angular separation (size perception) between the disks and their shadows could affect the strength of the depth separation illusion. To this end, we compared two different ways of nulling the illusion: intra-pair disparity modulation and angular separation modulation.

Methods.

The same stimuli as in Experiments 6 and 7 were used here, since adding the global disparity had no effect on the illusion. The two stimuli were shown in separate experimental blocks. The same seven observers participated in the experiment. They were tested on both the intra-pair disparity modulation, as used in the previous experiments, and the angular separation modulation, as given by formula (2) in Qian & Petrov (2012), in separate blocks.

Results.

Figure 18 compares the results using the two nulling methods. Since the added global disparity cue did not result in a significant increase in the perceived depth, the results of the two stimuli are averaged for each observer. On average, the required intra-pair disparity nulling is about 47% compared to the angular separation nulling, which is about 33%. The results show that both ways of nulling the depth illusion worked, but larger disparity changes than angular separation changes were required to null the illusion (F (1, 27) = 37.7, p < 0.001).

In other words, the angular separation modulation within disk pairs could cancel the depth illusion more efficiently than the disparity modulation. Similar to what we have found in
Experiment 5, the size/scale perception strongly modulates the depth perception. This may be due to the fact that angular separation (size) decreases linearly while disparity decreases quadratically with the viewing distance, and in order to null the same illusion, higher nulling amplitude of disparity is required than that of angular separation. In addition, it is consistent with our General Object Constancy model, since it predicts that the size perception could strongly modulate the depth perception.

Figure 18: Comparison between two different ways of nulling the illusory depth change. All seven observers were tested by both nulling paradigms. Two types of stimuli (Experiment 6 & 7 stimuli) were presented in separate experimental blocks, data of each observer were averaged for the two stimuli. The different colors indicate the different observers.

To further test this point, we replotted the data as correlation between the two conditions, shown in Figure 19. Disparity nulling (x-axis) and angular separation nulling (y-axis) of the
Figure 19: Comparison between disparity nulling (x-axis) and angular separation nulling (y-axis) of the depth separation illusion, measured by adaptively varying the relative disparity and the angular separation between the disks respectively. Each datum represents a different observer. The dashed line shows the diagonal. The red curve shows parameter-free predictions of the General Object Constancy model, \( y + 1 = \sqrt{x + 1} \) (see Appendix B).

The dashed line shows the diagonal. The red curve shows parameter-free predictions of the General Object Constancy model, \( y + 1 = \sqrt{x + 1} \) (for mathematical details see Appendix B). The data, which fall below the diagonal, demonstrates that a smaller amount of angular separation modulation than that of intra-pair disparity modulation were required to null the illusion. The red curve shows parameter-free predictions of the General Object Constancy model, \( y + 1 = \sqrt{x + 1} \). The data lie above the prediction curve means that the observers required a larger amount of angular separation modulation to null the illusion than that is calculated given by the model. This is because the size illusion inevitably comes into the depth separation judgment, even though we intentionally tried to eliminate its effect by asking the observers to judge the depth separation.
change during optic flow. On the one hand, the size illusion contributes to the depth separation illusion, since these two variables normally covary positively with each other in natural environments; on the other hand, the size illusion itself contradicts our expectation, since the angular size of an object normally decreases with viewing distance. These confounding factors may result in the differences between the theoretical prediction and the real observations.

5.5. Experiment 9: Effect of depth percept on the size illusion.

The results of the previous experiments indicate that the size illusion has significant influence on the depth separation illusion. One might ask whether depth manipulations can affect the size illusion. Specifically, can the size illusion be enhanced when the stimulus appears to have depth separation compared to the stimulus that appeared to be in the same depth plane? Establishing such a relationship would be suggestive to the way in which size and depth signals are processed by the hypothesized General Object Constancy mechanism.

Methods.

Two modifications of the shadowed disks stimulus were used in this experiment in separate blocks. Unlike all the previous experiments, there was no binocular disparity between the paired disks. The same three-dimensional percept was presented for one stimulus modification but not for the other. This allowed us to test whether depth percept would affect the size illusion in the absence of disparity cues. In the first block, the disk + shadow pairs (shadowed disks) were tested. Even with no disparity between the disks, the stimulus had the same 3D interpretation as in the previous experiments: a light disk was perceived in front of its shadow. In the second block, disk pairs of the same color, white or black, mixed in equal proportion, were used. The stimulus was perceived as two-dimensional: all the disks appeared to
be at the same depth. We referred to this stimulus as the ‘plain disks’. Five observers took part in this experiment, all of them perceived the stimuli as described above. Modulation of the angular separation within the disk pairs was used to null the size illusion in both blocks. For the shadowed disks stimulus, observers were asked to judge whether the separation within the disk pairs in a three-dimensional space increased during the contraction phase; for the plain disks stimulus, they were asked instead to judge whether the angular separation changed.

![Graph](image)

Figure 20: Comparison between the illusory separation change of the shadowed disks (y-axis) and the plain disks (x-axis). Each datum represents a different observer. The black straight line indicates the least-square function fit: $y = 1.075x$. No significant difference was found between the two conditions.

**Results.**

The magnitude of the size illusion for the plain disks is plotted on the x-axis and that for
the shadowed disks is plotted on the y-axis. Each datum represents a different observer. On average, the size illusion for the plain disks was about 17%, while for the shadowed disks was about 16%. The black line indicates the least-square linear fit: \( y = ax \), the slope \( a = 1.075 \pm 0.074 \). Even though the size illusion measured here was a little stronger than that measured in the previous study, about 15%, this could due to the individual differences among observers. The slope was not significantly different from 1 indicating that the depth separation perceived between the shadowed disks and the associated depth separation illusion had no effect on the size illusion (\( t = 1.04, p > 0.1 \)).

Even though the shadowed disks were perceived to have depth separation, it did not strengthen the size illusion. This is surprising, since normally, the change in depth separation is associated with the change in angular separation. This is what we found in Experiment 6, that the depth separation illusion is stronger than the veridical depth illusion because of the contribution of the size illusion. Also in Experiment 8, we demonstrated that the size manipulations had significant effect on the depth separation illusions. However, our previous study (Qian & Petrov, 2012) has shown that the size illusion strongly modulated the contrast illusion, while the contrast illusion had no effect on the size illusion. These results are explained by the General Object Constancy. Although counterintuitive, the results of this experiment are consistent with our previous study on contrast and depth gradient, that perceived size strongly affects contrast or depth gradient perception but not vice versa, supporting the General Object Constancy model.

5.6. Discussion

As in the previous chapter, the StarTrek illusion (Qian & Petrov, 2012) was used to explore the phenomenon of depth constancy in the current study. Using the ‘shadowed disk’
stimulus, we demonstrated a new illusion of the depth separation: an illusory variation of depth separation between the white disks and their shadows was observed during the optic flow motion. This was an even stronger illusion, 47% on average, compared to the depth gradient illusion, 43%. Experiment 8 showed that the depth separation illusion could be nulled by either intra-pair disparity modulation or angular separation modulation, and the angular separation nulling was more effective than disparity nulling. This suggests that the perceived size has a strong effect on the depth illusion. However, when binocular disparity was removed from the stimuli, maintaining a depth percept between the disks and their shadows did not strength the size illusion (Experiment 9). Experiment 7 showed that adding binocular disparity consistent with the optic flow motion does not enhance the depth separation illusion, consistent with our previous studies.

Even though we tried to eliminate the effect of size illusion by instructing the observers to judge the depth separation, it was still taken into account no matter how we formulate the task. It is somewhat expectable since laterally moving a cast shadow toward and away from the stationary target could induce an illusory depth change between the target and its shadow (Kersten et al., 1996). Only when the size illusion was physically cancelled, as in Experiment 2, could we measure the veridical depth illusion. Another way to find the veridical depth illusion was to calculate it given the depth separation illusion in Experiment 6 (Figure 16), and the calculation agrees with the results from Experiment 2.

In Experiment 7, we applied angular separation nulling to study the effect of size on depth separation illusion, instead of keeping the horizontal separation between the disks and their shadows constant as in Experiment 2. Compared to Experiment 6, which shows that 47% of disparity modulation was required to null the illusion, the angular separation modulation required
was only about 33%. The results are in accordance with our previous studies on contrast (Qian & Petrov, 2012) and depth gradient, where showed that the perceived size strongly modulated contrast and depth gradient perception.

On the other hand, this relation was not found in the opposite direction. Although we might expect that presenting a depth percept between the disks and their shadows could enhance the size illusion, since these two factors normally covary with viewing distance, we did not find such an effect in Experiment 9. However, it can be predicted by the General Object Constancy model, because the perceived size, serves as another scaling factor, in addition to viewing distance. We have already demonstrated that this factor was proportional to the perceived size change in the course of optic flow and significantly increased the contrast illusion and depth gradient illusion, compared to the size illusion. The effect of the objects size on its perceived depth profile revealed by the current study can be explained by the same size factor scaling the perceived depth separation (see Appendix B for more details).

The results from the current and the previous chapter are summarized in the following. We found a surprising correlation between the perceived size of an object and its perceived depth profile:

(i) The size illusion and the depth gradient illusion have a positive correlation, i.e., observer with a stronger size illusion has a stronger depth gradient illusion;

(ii) Across each observer, the strength of the size illusion is roughly half that of the depth gradient illusion measured when the perceived size remains constant, less than the depth gradient illusion measured when the size illusion is present;
(iii) The amount of angular separation modulation required to cancel the depth separation illusion is less than that of disparity modulation required.

(iv) Neither disparity modulation nor the depth percept affects the size illusion.

The results are compatible with the General Object Constancy model (Figure 21). In the previous chapter, we have demonstrated that the model bridges size constancy, depth constancy and contrast constancy similarly in a simple yet effective fashion. Since the brain employs a single scaling factor as a function of viewing distance for size and depth, result (i) can be explained. Additionally, the perceived size, serving as another scaling factor, further modulates the perceived depth. Both factors contribute to the depth perception by the second power. Because the size and depth are both scaled as a function of viewing distance, but the perceived size is further used to scale the perceived depth and not vice versa, therefore, the depth illusion ends up much stronger than the size illusion (see Appendix for mathematical details on result (ii) and (iii)). Because perceived depth does not come into perceived size calculations, this explains result (iv).

Our results imply that feature perceptions are essentially inter-correlated, because in everyday life, changes of these feature are associated with each other. Ecologically, it is possible that the neural substrates in the brain are wired to accommodate these associations. If features like size, contrast, and depth profile can be united by the General Object Constancy, why cannot other feature perceptions share a similar underlying mechanism? Color constancy, for instance, is often studied under various lighting conditions. However, the apparent color of an object also might change due to viewing distance. Aerial perspective cues is well-known of its contribution to the distance perception, additionally, it also might influence the color perception with changes
in viewing distance. Spatial frequency of an object, undoubtedly, is another feature that varies with viewing distance. We speculate that the General Object Constancy can account for other features besides size, contrast, and depth, such as color, and spatial frequency, etc...

![Figure 21: General Object Constancy mechanism. The brain scales disparity, retinal size and retinal contrast by a factor $k$ as a function of distance. Additionally, the perceived size change contributes another factor, $k'$, to the perceived contrast and the perceived depth. Both factors contribute to the depth perception squared to ensure depth constancy.](image)

5.7. Conclusions

The StarTrek illusion demonstrates several strong illusions across different feature dimensions, including size, contrast, and depth. In the previous chapter, we have studied the depth gradient illusion induced by optic flow; in a similar fashion, the depth separation illusion was investigated here.
We found that the depth separation illusion could be nulled by smaller angular separation modulation than intra-pair disparity modulation, suggesting that the perceived size has a strong effect on the depth separation illusion. A depth percept between the disks and their shadows but with no standing disparity in between could not affect the size illusion. These results further consolidate our findings that perceptions of size, depth, and contrast are related, supporting the General Object Constancy model. All three features are calculated from the corresponding retinal measures scaled by the same function of viewing distance. Moreover, the perceived size serves as a strong mediator that further scales retinal contrast and depth signals in order to calculate the perceived contrast and depth. Using the StarTrek illusion, the underlying mechanisms of size constancy, contrast constancy, and depth constancy are revealed.

Last but not least, our results imply that feature perceptions are inter-correlated, and it is possible that other features, besides size, contrast, and depth, also can be united into the General Object Constancy framework.
General Object Constancy reveals an intriguing relationship of visual perception across different feature dimensions. Nevertheless, there are many questions left to be answered. The findings on the relation of size and depth perception are surprising, but are there any other evidence that justify this hypothesis? What is the processing sequence of the constancy model? What are the neural correlates of the constancy mechanism? In this chapter, discussion regarding these aspects will be provided.

6.1. Relation of size, depth and distance

In order to evaluate whether the judgments of size, shape and distance are independent, Brenner & van Damme (1999) examined how adding information that improves one judgment influences the others. Observers adjusted the size and the global shape of a computer-simulated ellipsoid to match a tennis ball. The position of the simulated ellipsoid was then indicated manually. Adding information about distance improved the three judgments in a consistent manner, demonstrating that a considerable part of the errors in all three judgments were due to misestimating the viewing distance. Rotating the ellipsoid, thus providing information about shape, resulted in more veridical judgments of its shape (width, height and depth), but not of its size or position. Their results are in accord with the General Object Constancy model that size and depth perception rely on some common measures, such as that of viewing distance; while shape perception does not affect the size or distance judgments.

Brenner & van Damme (1999) did not test whether manipulation of the size could influence the accuracy of shape judgment, but Bradshaw et al. (1996) studied the effect of display size on disparity scaling from differential perspective and vergence cues. They found that
the differential perspective and the vergence of a blob-like surface independently affected its perceived depth and its size; these effects were additive, but their relative magnitudes changed with display size. Since subjective reports made by the observers indicated that perceived distance to the surface and the perceived size of the texture elements changed with changes in the viewing distance, they suggest disparity scaling may be achieve by first obtaining an estimate of the viewing distance and then using it to scale the horizontal disparities in order to calculate depth. This also agrees with our model, in particular, the manipulation of the display size also changes the perceived size of the stereoscopic blob-like pattern, indicating that the perceived size affects the depth scaling. Interestingly, they only found the effect when manipulating the differential perspective and vergence cues separately but not in combination, while in our model, as long as the viewing distance changes, the associated perceived size changes could influence the depth perception (note that this rarely occurs in natural viewing conditions, since the perceived size of an object remains constant with viewing distance), we have no satisfactory explanation for this discrepancy.

Another study (Collett et al., 1991) investigated how angular size and oculomotor cues interact in the perception of size and depth at different distances. In Collett’s study, observers looked through a darkened tunnel to see stereoscopically simulated 3D surfaces, thus oculomotor cues were principal cues to distance perception. They found estimates of the magnitude of a constant simulated depth dropped with increasing viewing distance when surfaces were of constant angular size. But with surfaces of constant physical size, estimates were more nearly independent of viewing distance – a demonstration of depth constancy. At any one distance, depth appeared to be greater, the smaller the angular size of the image. With most observers, the influence of angular size on perceived depth grew with increasing viewing distance. Based on
these results, they suggested that there are two components to depth scaling. One is related to viewing distance, and the other is related to angular size, and the weighting grows with viewing distance. They concluded that angular size and viewing distance interact in a similar way to determine perceived size and perceived distance. Their results could be explained by our model reasonably well. Because viewing through a darkened tunnel deprives the observer of other depth cues except vergence and accommodation, distance perception is less effective. Therefore, the angular size in this case is roughly equivalent to the perceived size (Holway & Boring, 1941), as we employed in our model. For the constant angular size condition, the size component does not affect the depth scaling, so the depth estimation is purely based on disparity signal and the vergence cue. However, the distance information derived from vergence cue cannot provide an adequate compensation for the loss of disparity signal, hence the perceived depth dropped with increasing viewing distance. For the constant physical size condition, the angular size decreases with distance. However, the texture (size and density) of the stimuli and overall size covaried with viewing distance, providing additional depth cues. In this case, the relative size, texture gradient and vergence cues work in coordination to yield a more reliable distance perception. Indeed, Collett noted in the paper that the correlated changes in retinal image size and texture with viewing distance seem to help make depth estimates more accurate. Even though the angular size decreases with distance, observers might use other coherent cues to judge the actual size of the stimuli, so the perceived size could still remain roughly constant. Therefore, it essentially makes the task similar to depth judgment under normal viewing conditions, which is nearly independent of viewing distance – depth constancy restored. In addition, the finding that the effect of size on depth perception grows with increasing viewing distance is also consistent with our model.
Some studies (Kaufman et al., 2006) argue that the same mechanism underlies perceived depth and perceived size, since the uncertainties (standard deviations) of size and depth judgments increased the same way as a function of distance. Our model does support that size and depth perception share a common process of distance scaling, in addition, size perception further affects depth estimation at a later stage of processing.

6.2. On the sequence of visual perception processing

There have been controversies on whether the retinal size is processed prior to distance information. Mckee & Welch (1992) studied the precision of judging objective size while assuming both that this task involves combined two independent processes of retinal size judgment and distance estimation, and that noise limits the discrimination of small differences in retinal size. According to their model, if the noise associated with distance estimating adds to the noise associated with encoding retinal size, the noise associated with discriminating differences in objective size should be significantly greater than that associated with discriminating differences in angular size, thus the retinal information is processed prior to encoding objective size. However, their observers were unable to ignore differences in depth when making angular size judgments, therefore they suggested that retinal size and distance are processed in parallel. In a later discussion McKee & Smallman (1998), they noted that angular thresholds for targets presented only in the fixation plane were significantly lower than the angular thresholds measured with random changes in disparity, showing that observers with normal stereopsis do not have direct access to information about the angle subtended at the retina. In other words, retinal size per se may not be available to conscious perception, a speculation consistent with some previous studies (Wallach & McKenna, 1960; Rock & McDermott, 1964). In our model, even though the retinal information is scaled by the perceived distance to achieve the objective
perception, we have no intention to suggest whether the distance cues are processed prior to or after the retinal information. Compared to McKee’s model, our model focus on the relationship of perception across different feature dimensions, instead of processing sequence of the distance perception and the retinal information processing.

6.3. Neural correlates of size constancy

Although computational theories on size constancy involving distance scaling have flourished based on psychophysical studies, its underlying neural mechanisms remain unraveled. In this chapter, we will examine neurophysiological and imaging studies which may reveal the neural mechanisms of size and depth constancy.

Single cell recordings in awake and anesthetized monkeys show that there are distance-dependent size tuning cells along the ventral pathway, from visual cortical area V1, V2 and V4 (Dobbins et al., 1998) leading to IT (Ito et al., 1995). In particular, Dobbins et al. (1998) found cells in V1, V2, and V4 were size-tuned and preferred the same retinal size regardless of distance: some showed a monotonic increase in mean firing rate with decreasing distance (nearness cell); some with increasing distance (farness cell); and some are distance-independent. These results imply that the distance scaling is necessary for size perception.

In addition, recent functional magnetic resonance imaging (fMRI) studies (Murray et al., 2006; Fang et al., 2008; Sperandio et al., 2012) demonstrated that the retinotopic representation of an object is modulated by its perceived size. In these studies, two 3D disks/rings were presented at either close or far apparent depth in a 3D scene. The distant object, which appears to be larger, causes a more eccentric activation in the primary visual cortex, compared to the apparently closer and smaller object, even when their angular size remains constant. In other
words, the same visual angle projected on the retina could occupy different proportions of V1 if the objects are perceived as being located at different distances (see Figure 22). Although these studies contradict the traditional view that retinotopic mapping in V1 is precise and hard-wired, emerging evidences (Liu et al., 2009) confirm that visual processing in V1 depends on both retinal image and distance information, which may be signaled by feedback of three-dimensional space representation from other visual areas, such as LIP (Gnadt & Mays, 1995).

Figure 22: Cortical activity of size perception. When a stimulus is present at a closer distance, the activity was strongest in the smallest eccentricity along the calcarine; when the stimulus with the same angular size (or an afterimage) is presented at a greater distance, the activity is stronger in the more eccentric areas. In other words, the bigger the stimuli appeared, the more eccentric the activation in V1. Red marks the smallest eccentric activation and purple marks the largest eccentric activation in V1.

Distance is a crucial process in preserving size constancy. Although there are many depth cues, such as binocular disparity, vergence, motion parallax, occlusion, familiar size, and linear perspective, given the limited distances and viewing conditions used in the single cell and imaging studies, one may conclude that disparity and vergence play a principle role in distance perception in these studies. Pioneering work on the cat visual cortex (Nikara et al., 1968;
Pettigrew et al., 1968) and later studies in a variety of species revealed that a large percentage of
cells in the primary visual cortex and extra striate areas are selective to horizontal disparity
(Hubel & Wiezel, 1970; Maunsell & Van Essen, 1983; Poggio et al., 1977; Poggio & Poggio,
1984; Poggio et al., 1985, 1988; Gonzalez & Perez, 1998; Cumming & DeAngelis, 2001), which
is often used to code for distance of an object from an observer, i.e., viewing distance. Poggio
classified disparity-selective neurons into three groups: Tuned cells are characterized by narrow
tuning with a peak close to zero disparity, and Near and Far cells showed broad tuning with peak
response at large values of disparity.

In addition, it is known that viewing distance can modulate neural responses of disparity
on the dorsal pathway from V1 to parietal cortex (Trotter et al., 1992; Maunsell & Van Essen,
1983; Takemura et al., 2001; Gnadt & Mays, 1995). For example, Trotter et al. (1992, 1996)
found that in alert, behaving monkeys, the responses of a large majority of disparity tuning
neurons in V1 was modulated by viewing distance. Specifically, the magnitudes of the responses
of disparity tuning cells in V1 were modulated by viewing distance, but the shape and position of
the peaks of the tuning curves were unchanged. Similarly, Gnadt & Mays (1991) found same
type of disparity tuning cells in the parietal cortex. Since it affected particularly disparity-related
activity and background activity and was not dependent on the pattern of retinal stimulation, they
suggested that extraretinal signals, probably vergence or accommodation, can be integrated with
disparity early in the visual processing pathway for the cortical representation of three-
dimensional space. This point was also supported by other studies (Foley, 1980; Collett et al.,
1991; Ogle, 1962). The phenomenon of such ‘gain’ fields for distance has been simulated by a
neural model that trained to calculate distance from pairs of vergence angles and disparity-tuned
unites proposed by Lehky & Sejnowski (1990). It is suggested that in area MT the integration of
the two signals takes place (Maunsell & Van Essen, 1983; DeAngelis et al., 1998; DeAngelis & Newsome, 1999). Monosynaptical connections from V1 to MT (Girard et al., 2001; Nowak et al., 1998) have been discovered in neurophysiology studies.

At a greater viewing distance, other depth cues, such as linear perspective or texture gradients, may dominate on distance perception. In this case, other visual areas can be involved. Single cell recordings (Liu et al., 2004) show inferotemporal (IT) neurons code for depth defined by disparity gradients and/or texture gradients. Theory has been proposed that IT integrates 1) distance information transmitted via superior colliculus-pulvinar afferents, with 2) form information transmitted via striate-prestriate cortex afferents. However, Ungerleider et al. (1977) trained monkeys to choose the larger of two objects independent of distance, and found that contrary to the theory, pulvinar lesions produced no deficit; and although prestriate lesions did produce an impairment, it was due to a failure to code distance in assessing the true size of the object. Thus, monkeys with prestriate lesions consistently responded to retinal image size instead of object size. Consistent with an earlier report (Humphrey & Weiskrantz, 1969), IT lesions also produced impairment, but errors were random and could not be attributed to any consistent strategy. These results indicate that there are multiple mechanisms available to the brain-damaged animal for the perception of size constancy.

Where is distance information coded? Single cell studies found that lateral intraparietal cortex (LIP) has a distributed representation of egocentric space (Gnadt & Mays, 1995; Andersen et al., 1985; Genovesio & Ferraina, 2004). It seems as if LIP receives inputs from MT and MST to obtain the distance information, and generates a three-dimensional space representation, which provides a premotor signal for directing saccades (Gnadt & Mays, 1995). We suggest that after information integration of disparity (arising from V1) and vergence (arising from FEF) in MT,
the signals feeds forward to LIP (Blatt et al., 1990; Genovesio & Ferraina, 2004) to construct the 3D space representation. Then, distance information feeds back to the MT (Ninomiya et al., 2012; Blatt et al., 1990), and even further back to V1, where it regulates responses of the size-selective cells to achieve distance-dependent size representation in V1 (Figure 22).

Some researchers suggest other neural mechanisms involved in size constancy. For example, Bishop proposed a neural model of depth constancy which involves size constancy as a pre-process stage; while size constancy is preserved by a feedforward process from mid-brain inputs through lateral geniculate nuclei, as discussed in the following section.

6.4. Neural correlates of depth constancy

Because depth constancy is normally considered to be operative at near viewing distances, as size constancy in laboratory setting, disparity and vergence are the principle cues for distance estimation. Bishop (1994) proposed a neural mechanism of depth constancy based on these two cues. In accord with our General Object Constancy model, he suggests that size and depth constancies are regarded as the first and second stages of a linked two-stage process.

In his proposed mechanisms, the innervation of the extraocular muscles, as signaled by the corollary discharge, provides information about the vergence of the eyes and hence about the distance both for symmetrical and asymmetrical vergences (Bishop, 1989). In the lateral geniculate nuclei, compensatory adjustments are separately applied to each retinal image as they are received from the two eyes, so that their horizontal and vertical dimensions are increased to offset the reductions in the sizes of the retinal images that occur at greater viewing distances. The modified retinal images, with their associated disparities, now provide synaptic inputs to binocularly activated cells in the visual cortex. Then, cortical cells with geniculate afferents with
vertical disparities will have their outputs expressed in terms of horizontal disparities. The horizontal disparity outputs of these cortical cells are then further multiplied by the outputs from cortical cells with geniculate afferents with horizontal disparities. It is this second multiplicative process that brings about the quadratic relationship between horizontal retinal disparity and distance. This quadratic relationship enables the perceptual system to offset the physical changes in the magnitude of the retinal disparities that are inversely proportional to the square of the viewing distance as described by the square law. Thus, he suggests in large measure, the stability of the visual world is brought about by the combined effects of the size and depth constancies.

Because our General Object Constancy model does not speak to the processing sequence per se, the controversies between suggested feedforward and feedback neural mechanisms cannot be resolved by the model. However, our model implies that size perception comes before depth perception, since the perceived size could contribute to perceived depth. It is worth to note that the neural mechanisms proposed by Bishop agrees with this implication that size and depth constancies are embedded in the first and second stages of a linked two-stage process.
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Appendix A

*General Object Constancy for depth gradient illusion.*

Let $s$ be the retinal separation and $\delta$ the binocular disparity between two points in space. Corresponding perceptual measures are given by the General Object Constancy model as follows. Brain first scales $s$ by a dimensionless factor $k$. $k$ is a function of the relative depth $d/d_0$, where $d_0$ stands for the reference viewing distance, e.g., the distance wherefrom the perceived motion in depth started in our optic flow paradigm. Based on our previous experiments (Qian & Petrov, 2012), function $k(d)$ is approximately linear for small motion amplitude factors. This is in agreement with the retinal size decreasing as a linear function of the viewing distance $d$. Correspondingly, $\delta$ is scaled by the square of $k$, because binocular disparity decreases as a square of the viewing distance, and therefore requires the squared factor $k$ to keep its percept invariant to the viewing distance:

$$S = s \cdot k \left( \frac{d}{d_0} \right)$$

$$D = \delta \cdot k^2 \left( \frac{d}{d_0} \right)$$

where $S$ and $D$ stand for the perceived size and depth respectively. In addition, Experiments 1 and 2 demonstrate that increasing perceived size (the size illusion) makes the perceived depth gradient illusion stronger. This is accounted by adding a factor $k'$ to the depth equation:

$$k' = \frac{S(d)}{S(d_0)}$$

$$D = \delta \cdot (kk')^2$$
where \( S(d_0) \) is the perceived size at the starting viewing distance \( d_0 \), and \( S(d) \) is the perceived size at the current viewing distance \( d \). In other words, the perceived depth is additionally scaled by the relative perceived size \( \frac{S(d)}{S(d_0)} \). Without a loss of generality we can assign \( k(1) = 1 \) and therefore \( S(d_0) = s(d_0) \) and \( D(d_0) = \delta(d_0) \). If the retinal size \( s \) remains constant (Experiment 2, size illusion), we obtain the illusion of the perceived size \( S \) as

\[
\frac{\Delta S}{S(d_0)} = \frac{S(d)}{S(d_0)} - 1 = k \left( \frac{d}{d_0} \right) - 1
\]

Because the perceived depth gradient (pencil’s sharpness) is defined as the length of the pencil tip (encoded as its perceived disparity) over its perceived size, \( D/S \), the depth gradient, \( DG \), is given by:

\[
DG = \delta \cdot k^2 \left( \frac{d}{d_0} \right) \cdot \frac{S(d)}{S^2(d_0)}
\]

Hence, we obtain for the strength of the depth gradient illusion (Figure 13) in Experiment 1:

\[
\frac{\Delta DG}{DG(d_0)} = \frac{DG(d)}{DG(d_0)} - 1 = k^2 \left( \frac{d}{d_0} \right) \cdot \frac{S(d)}{S(d_0)} - 1 = k^3 \left( \frac{d}{d_0} \right) - 1
\]

and therefore,

\[
\frac{\Delta DG}{DG(d_0)} + 1 = \left( \frac{\Delta S}{S(d_0)} + 1 \right)^3
\]

This relationship is plotted by the red curve in Figure 10. The red curve does not pass through all the data points, but given the large error bars, it is unclear whether the model needs revision.
Since the prediction is parameter free, any revision would have to be principled, rather than just by adjusting parameters. If the perceived size $S$ remains constant (Experiment 2, depth gradient illusion), we obtain for the depth gradient illusion,

$$\frac{\Delta DG}{DG(d_0)} = \frac{DG(d)}{DG(d_0)} - 1 = k^2 \left( \frac{d}{d_0} \right) - 1$$

Therefore,

$$\frac{\Delta DG}{DG(d_0)} + 1 = \left( \frac{\Delta S}{S(d_0)} + 1 \right)^2$$

This relationship shown by the black curve in Figure 10 fits the data very well given that the relationship is parameter free.
Appendix B

General Object Constancy for depth separation illusion.

From Appendix A, we have:

\[ S = s \cdot k\left(\frac{d}{d_0}\right) \]

\[ D = \delta \cdot \left( k\left(\frac{d}{d_0}\right) \cdot \frac{S(d)}{S(d_0)} \right)^2 \]

where S and D stand for the perceived size and depth respectively. This model is illustrated by diagram in Figure 21.

To null the depth separation illusion by means of the disparity modulation (leaving the illusory size change unaffected, Experiment 8), we require

\[ \frac{\delta(d)}{\delta(d_0)} = \frac{1}{k^4 \left(\frac{d}{d_0}\right)} \]

because then,

\[ D = \frac{\delta(d_0)}{k^4 \left(\frac{d}{d_0}\right)} \cdot k^2 \left(\frac{d}{d_0}\right) \cdot \left( \frac{S(d)}{S(d_0)} \right)^2 = \frac{\delta(d_0)}{k^2 \left(\frac{d}{d_0}\right)} \cdot (k\left(\frac{d}{d_0}\right))^2 = \delta(d_0) = \text{const} \]

To null the depth separation illusion by means of the angular size modulation (keeping the physical relative disparity constant, Experiment 8), i.e., \( \delta(d) = \delta(d_0) \) requires:
\[
\frac{s(d)}{s(d_0)} = \frac{1}{k^2\left(\frac{d}{d_0}\right)}
\]

then,

\[
\frac{S(d)}{S(d_0)} = \frac{1}{k^2\left(\frac{d}{d_0}\right)} \cdot k\left(\frac{d}{d_0}\right) = \frac{1}{k\left(\frac{d}{d_0}\right)}
\]

and

\[
D = \delta(d_0) \cdot k^2\left(\frac{d}{d_0}\right) \cdot \left(\frac{S(d)}{S(d_0)}\right)^2 = \delta(d_0) \cdot k^2\left(\frac{d}{d_0}\right) \cdot \frac{1}{k^2\left(\frac{d}{d_0}\right)} = \delta(d_0) = \text{const}
\]

Thus, to null the depth separation illusion by disparity nulling and angular separation (size) nulling, we can establish the following relationship between disparity and size modulation:

\[
\left(\frac{\delta(d)}{\delta(d_0)}\right)^2 = \frac{s(d)}{s(d_0)}
\]

and therefore,

\[
\frac{\Delta s}{s(d_0)} + 1 = \frac{\Delta \delta}{\delta(d_0)} + 1
\]

the fitting curve shown in Figure 18 is deduced from the above. It fits the data of Experiment 8 quite well given that the relationship is parameter free.