

3 Is There a Visual Space?

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ABSTRACT

The compelling phenomenological reality of visual space has rarely been questioned, let alone objectively tested, yet a unitary visual space stands as one of the key assumptions of most characterizations of human spatial vision. Here we evaluate the claim that all of our spatial judgments are determined by perceived locations of things in some personal phenomenal space. We show that if distortions of phenomenal visual space are spatially continuous (hence locally correlated) we can account for Weber's law in length judgments, as well as the fall-off from Weber's law observed at greater lengths. But experiments in the detection of a sinusoidal ripple fail to support the use of locations in a unitary space and suggest instead that features are located through distance or orientation measures relative to the objects to which the features belong. Experiments with the Zöllner and Müller-Lyer illusory figures fail to support the idea that apparent position completely determines apparent orientation (or vice versa). Instead, we suggest that special-purpose hardware underlies different spatial discriminations.

Feature space, color space, knowledge space: these all illustrate the use of spatial representation as an analytical tool in the effort to understand perception. But there is one *real* space in visual perception: the phenomenal space that represents the world as we see it; and no one doubts the psychological reality and spatial character of that. As Indow describes it, visual space is "the most comprehensive percept that includes all individual objects appearing in front of the perceived self" (Indow & Watanabe, 1988). It is the substrate for everything in the rich phenomenal world of visual experience. This space is also the subject of one of the most splendid and well-defined theoretical structures in psychology, the

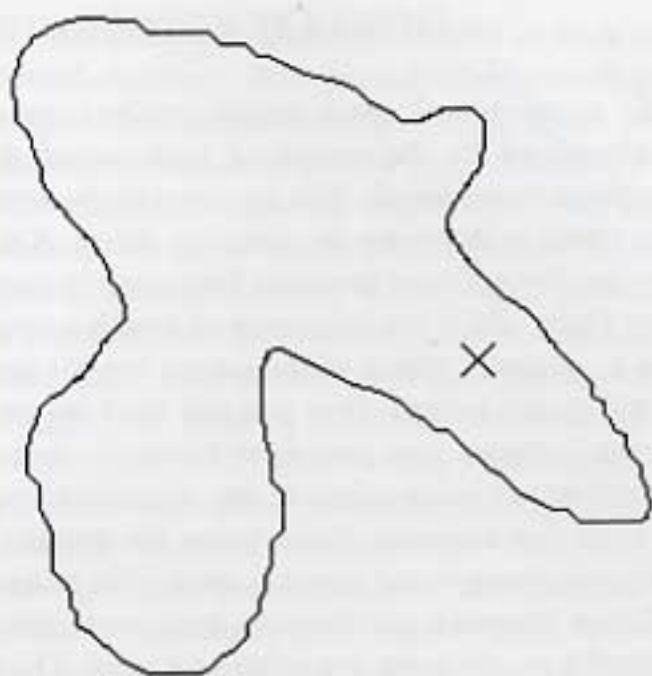
Luneburg model that Tarow Indow has done so much to expound and refine. But the aim of this chapter is to question the natural assumption that we experience a visual space. Can our visual experience of the world really be characterized as a sequence of apparitions occurring at definite locations in our personal visual space?

Obviously, in some sense the existence of visual space, and its genuinely spatial character, can hardly be doubted. You have merely to look around: surely being in a space is what vision feels like; or you can read the literature and find that mathematical models of visual space take it for granted. Although the spatial character of "visual space" has a compelling basis in experience, and is naturally embodied in geometrically formulated perceptual theories, it is not so obvious how (or whether) it can be objectively demonstrated or put to experimental test.

To proceed toward such a test, we first need to rephrase the point at issue in more definite terms. The claim we wish to evaluate is that our visual experience consists of nothing more than objects and events occurring in some personal phenomenal space. We take this to imply that *all of our spatial judgments, including judgments about such things as distance, movement, and orientation, are determined by perceived locations* of things in that space. In other words, all the spatial information to which we have conscious access is implicit in the changing perceived configuration of things in our personal visual space. We might call this the Tidy Mother model: the one necessary and sufficient principle for the organization of the phenomenal world is "a place for everything, and everything in its place."

The term "implicit in" could mean either that the derived spatial measures such as distance and orientation are directly given by the perceived locations of the features defining them, or that they are completely determined by those perceived locations. The responses of an observer in an experiment on spatial judgments cannot distinguish between these two possibilities; but the idea that distances, orientations, movements, and spatial frequencies are given *directly* by the configuration of things in subjective visual space can, we believe, be rejected as inadequate or incomplete on logical grounds. Suppose you are shown a closed curve (Figure 3.1) with some clearly visible feature inside or outside it. You would have no trouble pressing the correct button to indicate whether you are seeing the inside or the outside case. Now it could plausibly be maintained that you have in your head a representation of space where internal variables of some kind supply perceived coordinates, for each point on the curve and for the enclosed or excluded feature. But notice that with that assumption we still have not fully accounted for your ability to press the correct button. In fact, no one has ever, as far as we know, given a complete, connected, causal account of the ability of humans to perform this task. If you imagine being given a list of the physical coordinates of successive points as an intermediate result to work from, the difficulty of the remaining part of the job can be appreciated. It is just as hard

FIG. 3.1. Closed curve. Is the X inside or outside the curve? An easy discrimination. However, are the coordinates of the X and of the elements of the curve represented explicitly in some kind of internal model? What would the advantage of such a representation be over the representation present already at the level of the retina?



as the corresponding task for color space¹ where we usually consider the spatial representation to be only a metaphor. The initial replacement of physical coordinates with subjective coordinates is almost no help at all.

To acknowledge this difficulty, we might say that the "visual space" model under discussion requires a homunculus, who is left with the job of computing distances, orientations, etc., from perceived locations. If he (or she) does this using a consistent metric and without introducing further error in addition to whatever errors affect the perceived locations, we might be justified in taking the operations of the homunculus (or homuncula) for granted, by considering phenomenal visual space as the end product of the perceptual process. We require the homunculus to be infallible, because if that little person (or the equivalent perceptual or postperceptual mechanism) introduces substantial error of its own, you have to give up the key claim that the phenomenally registered positions of things in your visual space are what determine your spatial judgments.

With the "visual space" assumption thus defined, we now consider its experimentally testable consequences. We will deal first with a very simple case: the judgment of length or distance in the frontoparallel plane.

¹The corresponding task for color is as follows. You are presented with (1) a strip along which color varies continuously, perhaps along a complex curve in color space, as in Figure 3.1, returning at its far end to its initial color; and (2) a homogeneously colored test patch. You are asked, does the range of colors on the strip enclose the test color, or does the test color fall outside them?

A DIFFICULTY AT THE OUTSET: WEBER'S LAW

If, as the visual space model requires, perceived separations are completely determined by the perceived locations of the two objects or features whose separation is judged, then any error in the separation judgment must be traceable to errors in those two perceived locations. A difficulty for this model at the outset is that Weber's law holds (at least roughly: some of the relevant studies are listed by Ogle, 1962) for judgments of length or separation: the average absolute error is a constant fraction of the judged length, increasing in proportion to the length or distance judged. How can this be if the perceived distance is simply a difference between two perceived locations, and the variability in those perceived locations is independent of the distance between them?

We can reconcile Weber's law for distance with the visual space assumption by imagining visual space as analogous to an elastic ruler, subject to fluctuating forces that vary continuously both over time and across space, and that locally stretch or compress the subjective ruler. The perceived locations of identifiable points in visual space are read off from the ruler with some error that depends upon the ruler's current state. If the deformations of the measuring ruler are spatially continuous, the registered positions of two nearby points will tend to fluctuate together, rather than independently. The correlated component of the error in the registered positions of the two points will cancel when the subject (or the homunculus) evaluates the distance between them. The resulting distance estimate is relatively precise because only the uncorrelated component of error contaminates it. Moreover this uncorrelated component of error, and hence the error in the distance estimate, decreases as the physical separation between the points decreases, as Weber's law requires.

To see how we can get the quantitatively proportional relationship implied by Weber's law out of this, let \mathbf{x}_1 and \mathbf{x}_2 represent the horizontal positions of the two points in the observer's frontoparallel plane whose separation is being judged. The corresponding subjectively registered positions, \mathbf{x}'_1 and \mathbf{x}'_2 , are randomly perturbed from their mean values, \mathbf{x}_1 and \mathbf{x}_2 , by an error term with mean zero and variance σ^2 . The homunculus derives the subjectively registered distance between \mathbf{x}_1 and \mathbf{x}_2 without added error as $\mathbf{x}'_1 - \mathbf{x}'_2$. The variance of this is equal to $2\sigma^2(1 - \rho)$, where ρ is the correlation between the errors affecting \mathbf{x}'_1 and \mathbf{x}'_2 . The root-mean-square error in the distance estimate is the square root of that and is thus proportional both to σ and to $(1 - \rho)^{1/2}$. For spatially continuous deformations of the subjective ruler, the correlation ρ will increase smoothly toward 1 as the distance $s = \mathbf{x}_1 - \mathbf{x}_2$ between \mathbf{x}_1 and \mathbf{x}_2 decreases toward zero, and the factor $(1 - \rho)^{1/2}$, and hence the error, will decrease toward zero. This makes quantitative the intuitive expectation that the distribution of subjective separation measurements will become tighter as the judged separation decreases. For Weber's law, all that is needed is that $\rho(s)$, the spatial correlation function defining the correlation between the errors of position for points separated by s , be a bell-

shaped function of s or a smooth, monotonically decreasing function $|s|$ such as the positive valued lobe of a bell-shaped function. Then for sufficiently small s , $1 - \rho(s)$ will be proportional to the square of s , and its square root (and hence the root-mean-square error in the subjective estimate of s) will be proportional to s .

In two dimensions, similarly, we might compare the visual field with an elastic sheet undergoing spatially continuous deformations that introduce errors in spatial judgment. Another suggestive physical parallel is heat haze. As evidence that such deformations occur in perception, we note that quite pronounced continuous modifications of perceived shape are reported under the influence of mescaline (Kluver, 1966), and undrugged but fatigued observers sometimes report that the scene appears to "swim" noticeably. The mechanisms of such effects are not known, but there are some plausible candidates. Constancy-scaling mechanisms might impose a fluctuating scaling factor on regions of the visual field. On a slower time scale, topographic maps in the visual system are clearly plastic and are continuously revised and refined by experience (e.g., Kaas, 1987). Error-correcting mechanisms, or processes that reorganize the map to represent the range of spatial stimuli uniformly and efficiently (Kohonen, 1989) could inject time-varying deformations by continuously and locally readjusting the coordinate system.

A few years ago, Levi, Klein, and Yap (1988) suggested that Weber's law for spatial separation might be due to quite different factors. The precision of localization falls off from fovea to periphery, and this could limit the precision with which we judge large distances, because when you judge a large distance, at least one of the defining stimulus features must necessarily fall far from the fovea at any given time. They investigated the influence of this retinal position factor by presenting stimuli in brief flashes during fixation and ensuring that the eccentricity of the test stimuli was just as great for the small as for the large separation stimuli (see Figure 3.2). Their first results suggested that the precision of distance judgments in these isoeccentric presentations might actually be independent of the distance involved, in contravention of Weber's law. They therefore proposed that Weber's law arises (in less carefully contrived conditions) simply because errors of localization increase in proportion to retinal eccentricity. Such a proportionality would be consistent with a visual space that is logarithmically compressed, if the apparent positions of features in the compressed representation have a uniform statistical dispersion; and the complex log transform actually has good anatomical support as a rough idealization of the mapping from retina to cortex (Schwartz, 1980).

But this finding does mean the correlation-based elastic sheet model for length discrimination that we have been developing is in trouble—not for failing to predict Weber's law, but because it also predicts Weber's law under isoeccentric conditions, where, according to Levi et al., it is not found. Fortunately Levi and Klein (1990) have found in further work, prompted by contrary results from other labs (e.g., Morgan & Watt, 1989) and confirmed by our own observations,

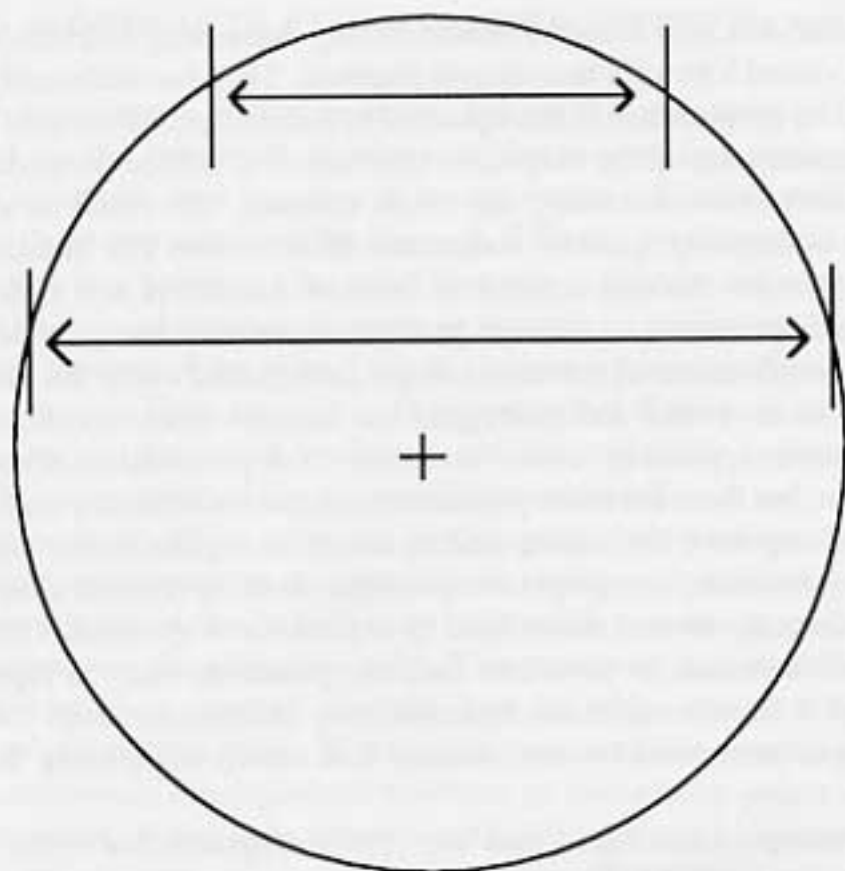


FIG. 3.2. Overview of the stimulus configuration used by Levi and Klein (1990). Each pair of vertical bars represents a given separation that subjects must evaluate. The bars always fall on the isoeccentric arc (made explicit here but not presented to subjects). Separations are judged relative to a remembered, reference separation.

that Weber's law can hold even at constant eccentricity, if the separations or distances judged are not too large. Their newer results, however, continue to show an unusual failure of Weber's law under constant eccentricity conditions, in that the precision of the judgment becomes asymptotically independent of the distance involved when that distance is large. This is consistent with the elastic sheet model. As the judged distance or separation becomes larger, it will eventually progress beyond the range across which positional errors are correlated. At that point, the errors in apparent position become practically statistically independent and the factor $1 - \rho(s)$ becomes independent of the separation s .

In Figure 3.3 we show the constant-eccentricity results of Levi and Klein (1990), fit by the elastic sheet model, assuming a simple bell-shaped form for the spatial correlation function for errors of localization: $\rho(s) = 1/(1 + (s/s_0)^2)$. The just reliably detectable length difference, Δs is obtained by substituting this expression of the spatial correlation function for localization errors into the expression $\sigma(2(1 - \rho(s)))^{1/2}$ for root-mean-square error:

$$\Delta s = (2\sigma^2)^{1/2} \left(\frac{(s/s_0)^2}{(1 + (s/s_0)^2)} \right)^{1/2}.$$

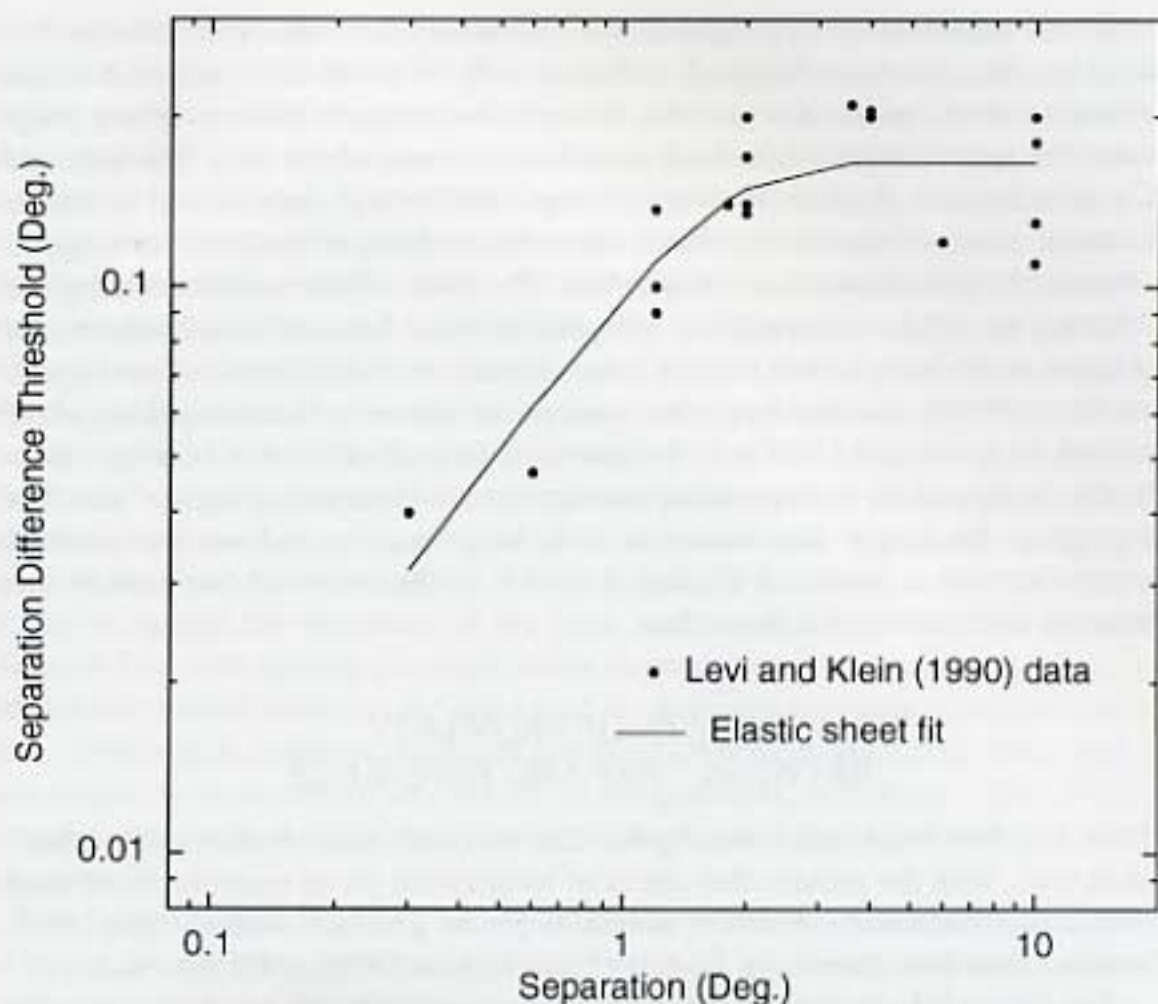


FIG. 3.3. Data of Levi and Klein, fitted assuming that errors of localization are spatially continuous, with the correlation function given in the text.

This correctly generates Weber's law for the isoeccentric condition for relatively small s , as well as the constant asymptote for large s . The best-fitting value of s_0 , the half-width at half-height of the spatial correlation function for errors of localization, was 1.45° of visual angle. An attractive aspect of the elastic sheet conception of visual space perception is that it similarly allows prediction of the precision of any spatial judgment once the spatial correlation function for errors of localization is given; but comprehensive analyses of this sort have yet to be undertaken.

This general approach to the statistical analysis of spatial judgments is far from new. Cattell (1893) started from the assumption that errors of subjective magnification, rather than of subjective position, occur independently at different positions within the field of view. He showed that the error in length discrimination should then increase as the square root of the length judged rather than in direct proportion to it. This introduced the "square root law" into psychology. Following a suggestion of Fullerton, Cattell also showed how Weber's law would arise instead, provided only that the errors of subjective magnification for differ-

ent small segments of the judged line are positively correlated over trials—they need not be perfectly correlated, but need only be positively correlated on the average over all pairs of segments. Weber's law emerges because in any judgment the same error tends to be repeated for all parts of the line. Fullerton and Cattell's account in terms of errors of magnification is closely related to ours in terms of errors of apparent position, since the correlation functions for magnification and for position are interdependent. The main differences between the two schemes are (1) for compatibility with Weber's law the correlation function for position errors must be bell shaped, whereas the correlation function for magnification need only generate a positive average correlation between segments of the judged distance; and (2) if it is the errors of magnification that become statistically independent at large separations, we would expect a square root law asymptote for length discrimination with long lengths, and not the constant asymptote that is predicted (Figure 3.2) if it is the errors of localization that become asymptotically independent.

EFFECTS OF PROXIMITY BETWEEN TEST AND REFERENCE

Thus far, the visual space assumption has survived confrontation with experiment well, with the proviso that errors of localization (or of magnification) must fluctuate continuously across space in order to generate Weber's law. Next, however, we introduce some findings that create difficulties for the model.

The Weber's Law experiment itself generates a difficulty on closer consideration. In the above analysis, we have implicitly assumed that the just noticeable difference in distance is proportional to the standard deviation of the judged distance. In practice, however, the just noticeable difference is almost always determined by comparing two distances. To be reliably detected, a difference in distance must exceed the standard deviation of the *difference* between the perceived values of the two distances compared. This introduces once again the same statistical considerations that arise in the relation of perceived distance to perceived locations of the defining pair of features. The variability of the distance-difference is dependent on the correlation between the two perceived distances, and on the model under discussion this will depend on the spatial separation between the test and comparison lines or between the two defining pairs of features. In fact, with a bell-shaped correlation function for position, the expected outcome is (as we hope to show elsewhere) the proportionality of the just-noticeable difference in distance both to the judged distance (as implied by Weber's Law) and to the test-to-comparison distance. The latter proportionality is not generally observed, even approximately: proximity of test and comparison stimuli does not improve distance discrimination in the way required by the visual space assumption (Andrews, 1967; Lennie, 1972).

We have looked at this problem in the context of what Tyler (1973) calls

"periodic vernier acuity." Tyler found that a horizontal line with minimal vertical sinusoidal ripple could be discriminated from a straight one if its peak-to-peak vertical excursion was (over some range) a constant fraction of its horizontal spatial period. Tyler's interpretation was that the subject requires a minimum orientation variation along the line for detection of the ripple. Alternatively, however, his result can be predicted from the elastic sheet model without invoking any representation of orientation as such and without abandoning the visual space assumption. We need only suppose, by analogy with our treatment of Weber's Law for length, that the correlation of vertical errors of localization is a bell-shaped function of horizontal (as well as vertical) distance. Now if this is the correct explanation for Tyler's result, we might expect that an adjacent, straight "landmark" or reference line would improve performance, particularly under conditions where the separation between the landmark and the sinusoid is much less than the period of the sinusoid. In this landmark condition, subjects should be able to assess the distances of the peak and trough of the test line to the reference line with greater precision when those distances are relatively small, and this cue should undercut the one based on comparisons made along the sine wave. However, in experiments to test this point (Willen & MacLeod, 1991), we were unable to demonstrate any benefit of the landmark or reference line, even when the distance to the reference was much smaller than the spatial period of the test sinusoid.

This failure to benefit from a nearby reference line in the detection of sinusoidal ripple is consistent with a model like Tyler's in which orientation-sensitive mechanisms process the test line (more or less independently of its context, almost as if landmark and test were in separate spaces) for signs of ripple. But it is difficult to reconcile with our alternative, in which ripple detection depends only upon the appropriate use of subjective locations in a unitary space that have been perturbed by spatially continuous error.

More generally, measures of such things as distance and orientation derived from each judged stimulus object (Baylis & Driver, 1993; Lennie, 1972; Watt, 1988) may be contaminated by errors that are not traceable to localization errors, but instead originate in the neural representation of the derived quantity (e.g., distance or orientation). Such errors need not show the proximity-dependent correlation required by the visual space assumption. Physiological observations also support the orientation model, inasmuch as visual cortex is packed with orientation-selective neurons. We next consider some other possible psychophysical consequences of that.

FRAGMENTATION: ZÖLLNER AND MÜLLER-LYER FIGURES

The current picture of visual processing suggested by anatomy and physiology is indeed the antithesis of the one favored by naive realism on the one hand and

mathematical psychology on the other. Anatomy and physiology have revealed a plethora of specialized mechanisms for representing such specific spatial attributes as orientation, motion and spatial frequency. It would be surprising if those different representations were not each subject to their own systematic biases and their own sources of random error. But where in this confusingly complex scenario, with its independent and potentially inconsistent representations of different elements, is visual space? Is it possible that we construct a coherent, self-consistent spatial representation from all these potentially inconsistent signals, much in the way that Ullman's (1984) model for structure from motion takes the results of different local analyses and tries to fit them together?

We have examined the mutual consistency of perceived distance and orientation, in an experiment in some ways resembling the alley experiments which in Blumenfeld's (1913) hands originally provided the main basis for the Luneburg model. There a Riemannian geometry was invoked to explain what in Euclidean geometry would have been an inconsistency. But we use frontoparallel presentation with small fields, where Indow (1991) has found that the Euclidean description is valid with great precision. Our question is whether a geometrical illusion figure can create an inconsistency between distance and orientation judgments: first for the Zöllner figure and then the Müller-Lyer figure. The Zöllner figure is usually regarded as an orientation illusion, the Müller-Lyer as one of length. We wished to examine the mutual consistency of judgments that might depend on assessments of orientation or on length when these figures are viewed.

Our Zöllner stimulus (Figure 3.4) was composed of illuminated lines on a CRT screen. Subjects adjusted the vertical separation of the central pair of dots in this figure to match the separation of the upper or lower endpoints of the nearly vertical lines—the apparent orientation of which is normally distorted by the oriented crossing lines of the Zöllner figure. We compared the settings for the two ends of the illusory taper, to yield a measure of the illusion's effect on the apparent position of the ends of the lines. In a separate phase of the experiment, we also asked subjects to adjust the orientations of the vertical lines so that they were subjectively parallel. Thus, we have both a position-based measure of the extent of the illusion and an orientation-based measure of the extent of the illusion. These will be consistent only if lines judged subjectively parallel are also judged equidistant. Our data so far are somewhat equivocal. In the average over subjects, the positional measure and the orientation measure are quite consistent, a result that seems surprising if one assumes, as physiology invites one to do, that orientation is represented more or less independently of position in visual processing. There is, however, significant individual variation among subjects, with some subjects demonstrating statistically significant differences ($F(10,202) = 3.72, p < .0001$) between their parallelism and positional settings, different in direction for different subjects.

For the Müller-Lyer figure, we similarly asked subjects to set the vertical separation of a pair of dots equal to the horizontal length of the upper or lower

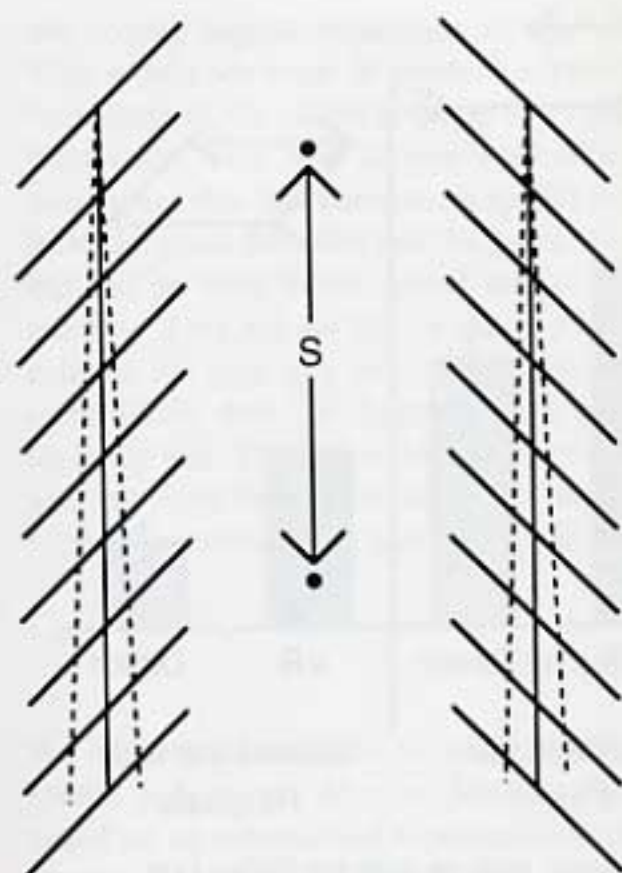


FIG. 3.4. Zöllner figure. Subjects were asked to adjust the separation between the vertically separated dots so that it would match the distance between the specified (either upper or lower) endpoints of the (nearly) vertical lines. The actual orientation of the vertical lines varied randomly within a small range (indicated by the dashed lines), but the relevant endpoints were always fixed to be the same distance apart.

lines in the Müller-Lyer stimulus presented as part of Figure 3.5. Subjects were also asked to adjust the length of the two lines to be subjectively equal to each other while viewing exactly the same stimulus. To make the orientation judgment more explicit, we then added lines connecting the endpoints of the horizontals and asked subjects to again make a comparative separation judgment, and again to set the horizontals to be of equal length.

In the control condition where no Müller-Lyer inducing lines are present, the results of the two types of judgment were fully consistent. Small but statistically significant ($F(1, 9) = 5.63, p < .05$) differences emerged, however, when the illusion was in force (Figure 3.5), with a tendency for conditions in which orientation was made salient to show less illusion than those where distance was assessed with a vertical reference dot pair, and/or where no parallels were provided in the stimulus. This supports the notion that the Müller-Lyer illusion is to some degree specific to distance judgment, and is not consistently reflected in perceived orientations within the figure.

In a further experiment with the Müller-Lyer figure (without physically present parallels) we asked subjects to make two different settings: the usual setting for equality of length, and a setting for parallelism of imaginary lines connecting the endpoints. The results uphold the statement made without supporting evidence in Suppes, Krantz, Luce, and Tversky (1989, p. 135) that the illusion is

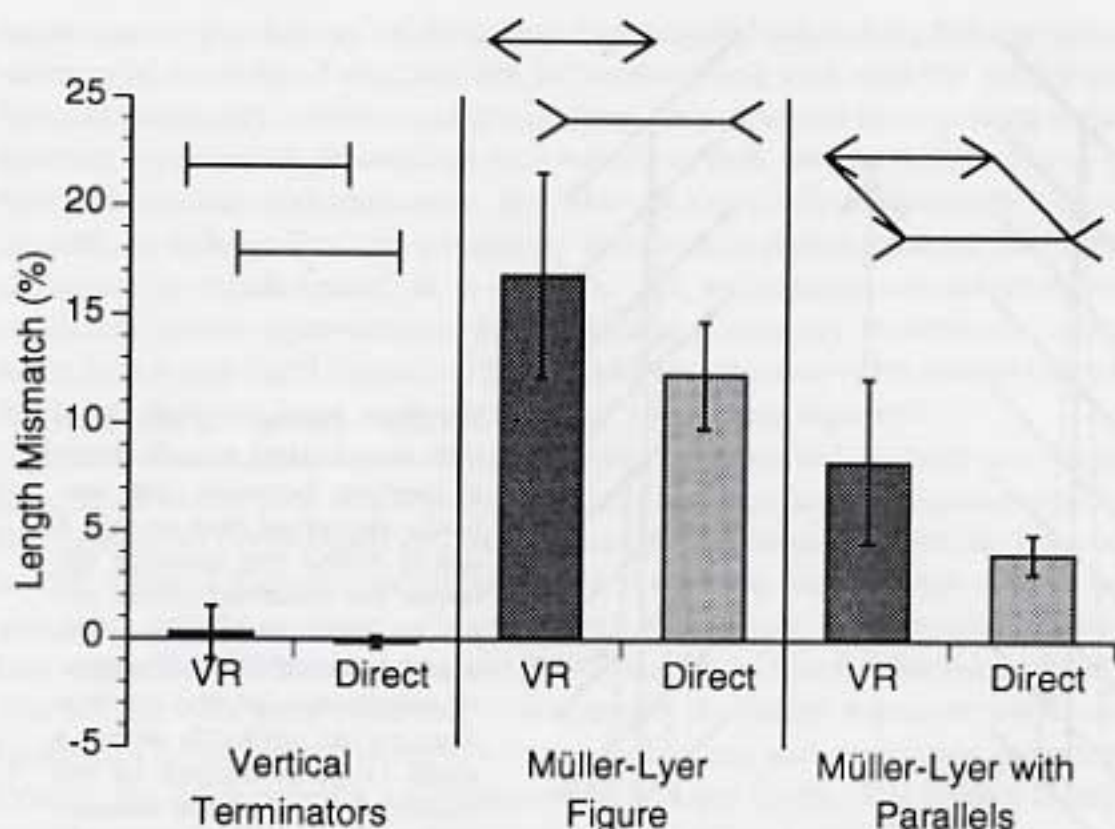


FIG. 3.5. Length mismatch in subjects' settings with the Müller-Lyer figure (displayed above the data for each condition) as measured by comparison of the indicated length to a vertical reference (VR) pair of dots, or as measured by directly adjusting (Direct) the length of the horizontals in the figure. The horizontal and vertical positions of the two lines was varied randomly from trial to trial within a limited range.

less apparent in the parallelism judgment. The length mismatch was 15% in the settings of the vertically separated reference dot pair, but only 11% in the parallelism settings. Thus, there was a difference of approximately 3–5 percentage points in length mismatch between the parallelism and equal length settings, averaged over subjects. Again as in the Zöllner case, individual subjects made parallelism and equal length settings that differed systematically in one direction or another ($F(9,760) = 6.46, p < .0001$).

Thus, in both the Zöllner and the Müller-Lyer cases, the results for individual subjects cannot be said to support the idea that apparent orientation is completely determined by apparent position (or vice versa). However, the overall approximate consistency of the orientation and position judgments could support an alternative scenario in which each subject's visual system tries (without complete success) to generate a unitary spatial representation that strikes a good single compromise between inconsistent reports about orientation and position.

So this evidence suggests either that there is no reconstruction of a unitary visual space, or else that an attempt to reconstruct one from independent data about orientation and position is made but without complete success. But there

are cogent logical objections to any reconstruction-of-visual-space scenario. Why would we want to produce such a reconstruction? Useful processing has been done in the visual pathway to explicitly encode spatial frequency, motion, orientation, and who knows what other behaviorally useful information. To merely use this to reconstruct a spatial representation would be to cancel (doubtless with great difficulty) all the gains of all that preconscious perceptual processing and go back to the retinal image. We would then need the homunculus as much as if we did not have a visual cortex. Conversely, that nonexistent homunculus is the only guy who needs a reconstructed unitary visual space. It seems more likely that the fragmentation physiologically revealed is also psychologically real. Doubtless the results of different local computations have to interact, but their interaction need not, should not, and probably does not take the form of constructing a unified spatial representation.

CONCLUSIONS

We are left with a view in which special-purpose hardware underlies different spatial judgments. Motion detection by direction-selective cells need not be based on an internalized representation of position any more than a car's speedometer reading or a Doppler shift speedometer requires such a representation. Similarly, orientation mechanisms need not internalize positional measurements. A complex cell in primary visual cortex (or more strictly a collection of them) is probably as good an example as any of a device that represents orientation without retaining information about position.

Visual experience provides its own support for this counterintuitively fragmented conception of spatial processing. A few examples to add to the experimental results reviewed above: first, it is a familiar observation that the motion after-effect is subjective motion often unaccompanied by subjective translation, presumably because it originates in activity specific to a motion-signaling system (Gregory, 1990). Second, the spatial-frequency after-effect of Blakemore and Sutton (1969) and the similar simultaneous induction effect of MacKay (1973) are situations in which particular types of feature (e.g., grating stripes) undergo perceptual expansion or contraction without a geometrically consistent perceived expansion or contraction of the window in which they appear. Third, the impossible objects of Penrose and Penrose (1958), and the prints of Escher, in which first one and then another representation is constructed from local and fragmentary information, or the Frazer spiral, which is really a circle but can never look like one, indicate that the phenomenal integrity of visual space is itself an illusion. The sense of paradox in these cases arises because we think, at any moment, that we have a complete and consistent spatial representation of what is out there, when in fact we have no such thing, but are incorrectly inferring the whole from fragmentary information.

The mother of all illusions is the illusion of objectivity. A part of that may be

the illusion of spatiality: the notion of a perceived visual space, natural though it is, may not capture important realities of visual space perception. Visual space perception starts with a space, but it probably does not end with a space.

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