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The Visual Perception of Three-Dimensional Length

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A set of 4 experiments evaluated observers' sensitivity to three-dimensional (3-D) length, using both discrimination and adjustment paradigms with computer-generated optical patterns and real objects viewed directly in a natural environment. Although observers were highly sensitive to small differences in two-dimensional length for line segments presented in the frontoparallel plane, their discrimination thresholds increased by an order of magnitude when the line segments were presented at random orientations in 3-D space. There were also large failures of constancy, such that the perception of 3-D length varied systematically with viewing distance, even under full-cue conditions.

During the past 100 years, there have been numerous investigations of the geometric relationship between physical and perceived space. Although it may be tempting to assume that perception is veridical on the basis of the success of visually guided action, research has shown that the subjective appearance of three-dimensional (3-D) form can be systematically distorted even during binocular observation (for a review, see Foley, 1980). The geometrical perceptual illusions are an interesting case in point, because they illustrate that the relationship between physical reality and perception may not be as simple as it appears at first glance.

Physical spatial relations, over the range relevant for human observers, can be well described using the tools of euclidean geometry, and it is therefore natural to assume that the perception of spatial layout is euclidean as well. The hypothesis that perception is euclidean has at least two meaningful interpretations. With appropriate methodological procedures, it is possible to measure the intrinsic structure of perceptual space without making any reference whatsoever to the external environment (e.g., see Blank, 1961; Foley, 1972, 1991). Perceived 3-D structure would be euclidean in that context if judged distance intervals in different directions satisfied the Pythagorean theorem. It is also possible to measure the extrinsic structure of perceptual space by measuring how observers' perceptions are mathematically related to the true physical structure of objects in the environment (see Tittle, Todd, Perotti, & Norman, 1995). Using an extrinsic analysis, observers' perceptions would be euclidean if the mapping between physical and perceived space does not distort lengths or angles.

It is especially interesting to note in this regard that it is mathematically possible for the intrinsic structure of perceptual space to be euclidean even though the extrinsic relationship between physical and perceived space is demonstrably noneuclidean. Indeed, this hypothesis has been proposed by Wagner (1985). According to this view, the perception of 3-D form could involve explicit euclidean representations of lengths and angles, which are systematically distorted relative to the true physical environment. Throughout most of the present article, we will restrict our discussion to the extrinsic structure of perceptual space, although we will present one experiment that examines its intrinsic structure as well.

There are two critical properties that need to be satisfied to conclude that perceptual knowledge of spatial relations is extrinsically euclidean. If a line segment is rotated in euclidean space, its length remains invariant. The same is true for translations. Both of these properties must be fulfilled, by definition, for any situation in which euclidean geometry applies.

One can assess in one of two ways whether euclidean geometry adequately describes how people perceive spatial relations: (a) present equal physical lines in different orientations, different positions, or both and evaluate whether the resulting perceived lengths are also equivalent or (b) given one length in one particular position and orientation, adjust another length in a different position, a different orientation, or both until it appears perceptually identical and then evaluate whether the two perceptually equivalent intervals are also physically identical. If equal physical lengths also appear the same perceptually, then in psychological terms, this phenomenon would be referred to as length constancy.

In general, research conducted over the last century (see Baird, 1970, for an excellent review of the early literature on this topic) has found that the perceived length of a physical interval is influenced by its position and orientation in space, contrary to the axioms of euclidean geometry. Specifically, there is a sizable body of evidence to indicate that intervals in depth are perceived differently than those oriented in the frontoparallel plane. This result has been found for computer-generated patterns presented during reduced-cue conditions (Johnston, 1991; Tittle et al., 1995) and for real objects viewed directly in a full-cue environ-

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ment. Researchers investigating the phenomenon of size constancy have shown that the apparent frontal size (e.g., width or height) of an object tends to become slightly larger as viewing distance is increased (Carlson, 1962; Holway & Boring, 1941). However, physically equal intervals in depth along an observer's line of sight appear increasingly compressed the farther from the observer they are presented, even in open outdoor environments where there are many available sources of optical information (Gilinsky, 1951; Harway, 1963).

Several investigators (Baird & Biersdorf, 1967; Gogel, 1960; Wagner, 1985) have found constancy or slight overconstancy for frontal intervals and systematic compressions of intervals along the line of sight. The amount of compression of intervals in-depth relative to those in the frontoparallel plane increases continuously with viewing distance, so that for far viewing distances (20–40 m), in-depth intervals appear to be only half as large as physically identical intervals in the frontoparallel plane. All of the aforementioned experiments were conducted in well-lit environments. For example, Wagner's investigations took place outdoors in an open grassy field, whereas Baird and Biersdorf found significant amounts of perceptual distortion within near visual space on a tabletop (i.e., less than 2 m).

Heine (1900), Loomis, Da Silva, Fujita, and Fukusima (1992), and Thouless (1931) required observers to simultaneously match in-depth intervals with frontoparallel intervals. Heine's observers adjusted three vertical rods at different viewing distances to form an equilateral triangle in depth in a well-illuminated room. To accurately perform this task, the observers needed to scale the depth of the triangle relative to its horizontal base. Heine found that observers could accurately adjust the triangles only for very near viewing distances (approximately 33–50 cm). At farther viewing distances, observers created triangles that were physically distorted. At distances between 1 and 2 m, all observers produced physical triangles that were exaggerated in depth by 50–100%, reflecting large perceptual compressions. At the closest distance, 1 observer adjusted the physical triangles to have too small an extent in depth, indicating a perceived expansion. Loomis et al. and Thouless also found that perceived space was increasingly compressed in depth at farther viewing distances. Heine's and Thouless's experiments were conducted within near visual space (2 m or less), whereas Loomis et al. used intermediate viewing distances ranging from 4 to 12 m.

The fact that in-depth intervals are scaled differently than frontal intervals has important consequences for the discrimination of length in more general situations. The apparent length of any given line is a function not only of its actual length but also of its orientation and position in space. Orientation is a factor because some orientations are subject to distortions (parallel to the line of sight) whereas other orientations are not (frontoparallel). Position in depth is also a factor because in-depth intervals are increasingly compressed at farther viewing distances. All intervals with some component in depth are then subject to this distortion to varying degrees. Therefore, in a length discrimination task, observers should be relatively accurate for lengths having the same orientation with respect to the frontoparallel plane at a given location in depth, less accurate for lengths having differing orientations at a given location in depth, and least accurate for differently oriented lengths presented at different distances. Such failures of constancy for lengths presented in differing orientations and distances, if found, would constitute strong violations of euclidean axioms. We wanted to determine whether human observers could perceive lengths in a euclidean manner under any set of circumstances. Toward this end, we used multiple simultaneous sources of optical information to redundantly specify the length intervals to be compared. We used both discrimination and adjustment tasks to provide converging evidence about human performance. All tasks were performed in near visual space. In some experiments, we used depth intervals in physical space rather than simulated computer-generated intervals on a CRT.

Experiment 1

The purpose of this experiment was to assess whether observers perceive two-dimensional (2-D) lengths in a euclidean manner. If so, then observers should be able to compare lengths that are in different positions and orientations in the frontoparallel plane. The distortions of visual space reported by Baird and Biersdorf (1967), Gilinsky (1951), Harway (1963), Loomis et al. (1992), Thouless (1931), and Wagner (1985) should not affect the discriminations of 2-D lengths in the frontal plane because the compressions of visual space take place along an observer's line of sight.

In the 19th century, researchers found that thresholds for 2-D length discriminations were fairly low. The Weber fractions were typically around 1–3% (Fechner, 1889, pp. 211–217; Volkmann, as cited in Helmholtz, 1925, p. 169; Weber, 1965; see also Wundt, 1892/1901, pp. 150–151), representing relatively good human performance but more than an order of magnitude above Weber fractions obtained for other tasks, such as tonal pitch discrimination. Most of these experiments involved comparisons between parallel lines. Therefore, one cannot conclude from these early experiments that the perception of 2-D length in the frontoparallel plane is euclidean. Indeed, the 19th-century researchers found that when they compared nonparallel line segments, the discriminations became much more difficult (Helmholtz, 1925, p. 175). This performance deterioration reflects, in part, the vertical–horizontal illusion, where vertical lines appear longer than horizontal lines of the same length.

To fully test whether perception of 2-D length is euclidean in nature, one has to compare the discriminability of line segments oriented in different random directions with that obtained for parallel line segments. There should be no difference between these two conditions.

Method

Observers. There were 3 observers, all of whom were authors: J. Farley Norman (J.F.N.), James T. Todd (J.T.T.), and Victor J.

Perotti (V.J.P.). All observers had normal or corrected-to-normal vision.

Apparatus. The optical patterns were created and displayed on a Silicon Graphics 4D/310 VGX workstation. The viewing distance was 85.0 cm, such that the display screen was 1,280 pixels wide × 1,024 pixels high and subtended 22.6° × 18.2° of visual angle.

Stimulus displays. The stimulus patterns were red line segments presented against a black background. Anti-aliasing hardware was used in drawing the line segments so that the positions of the endpoints were more precisely defined than pixel resolution. The effective resolution in this case was at least 0.1 pixel. The line segments were 2 pixels wide, which was 2.15′ of arc at the 85-cm viewing distance.

Two line segments were presented during each trial presentation. A two-alternative temporal forced-choice discrimination procedure was used in conjunction with the traditional method of constant stimuli. The line segments to be presented during a given trial were either parallel or randomly oriented over the full range of 360°. Parallel and randomly oriented lines were presented during separate experimental blocks. There were two standard line lengths, 6.0 cm and 9.0 cm, which were also presented in separate blocks. There were, therefore, four blocks (2 × 2 factorial design) within each experimental session. Within each block, there were eight test line lengths to be discriminated from the standard, four shorter than the standard (shorter by 1.0%, 3.5%, 6.0%, and 8.5%) and four longer than the standard (longer by 1.0%, 3.5%, 6.0%, and 8.5%). There were 20 replications of these eight basic conditions, producing 160 trials per block. Five experimental sessions were run for each observer. Therefore, 100 trials were obtained for all conditions. Each observer followed a different random order of the four blocks within any given experimental session.

Procedure. On any given trial, the observers' task was to decide whether the longer line segment was presented during either the first or the second temporal interval. After the initiation of a trial, the observer saw the first temporal interval's stimulus for 1.5 s, followed by a 1.5-s blank pause. The second temporal interval's stimulus was then displayed for 1.5-s. Following the disappearance of the second interval's stimulus, the observer recorded his response using different buttons on the workstation's mouse. Auditory feedback (a short beep) was provided after each correct response. The standard length was shown to the observer prior to the start of each block of 160 trials.

Results and Discussion

The psychometric functions for each observer are shown in Figure 1. Separate functions are shown for the parallel and random orientation conditions. We combined the results for the 6.0-cm and 9.0-cm standard lengths because we found that our discriminations obeyed Weber's law—the absolute magnitude of the standard did not make any difference. The smooth curves represent the best fitting cumulative normal (ogive) for each empirically determined psychometric function. We calculated the probit fits and thresholds using a program developed by Foster and Bischof (1991).

The threshold difference to detect lengths longer than the standard is indicated by the 75% point on the observers' psychometric functions. Similarly, the 25% point reflects the threshold difference necessary to reliably detect lengths shorter than the standard. The overall length difference

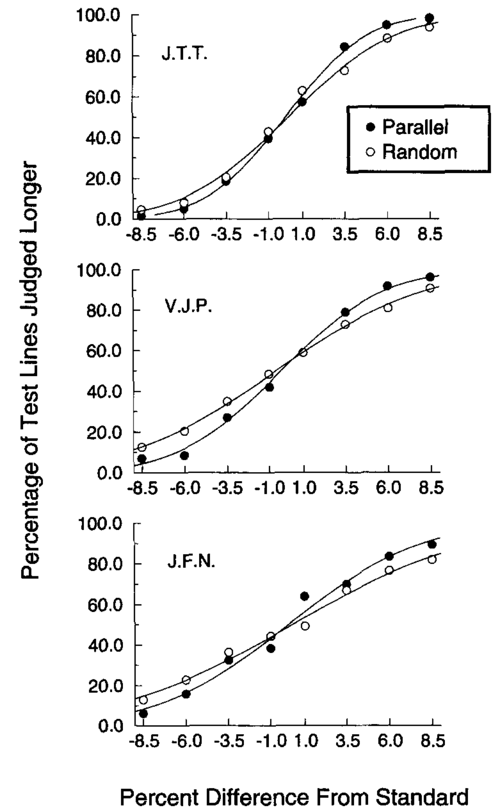

Figure 1. Individual psychometric functions from Experiment 1 for the 3 observers (represented by initials). Parallel = parallel orientation condition; random = random orientation condition.

thresholds for each observer were calculated by taking the average of the magnitudes of these two difference thresholds relative to the standard. Observers J.T.T., V.J.P., and J.F.N. needed 2.53, 3.25, and 4.16% differences, respectively, to reliably discriminate parallel lengths. For the randomly oriented lengths, the thresholds for the same observers were 3.32%, 4.68%, and 5.69%, respectively. It is readily apparent that for the parallel line segments, we obtained results similar to the classic results described by Wundt (1892/1901, pp. 150–151). The thresholds and the psychometric functions for the randomly oriented line segments show a deterioration in performance. Threshold estimates for the randomly oriented lengths were about 37% higher than those for the parallel lengths. Although we did not explicitly test for it, we strongly suspected that this increase was due to the well-known illusion that vertical lines appear noticeably longer than horizontal lines that are physically equal in length. All 3 observers noted that during the course of the experiment they frequently responded with confidence that a vertical line appeared longer than a horizontal one in the random orientation condition and then received feedback that this response was incorrect.

Experiment 2

A key test of whether human observers generally perceive lengths in a euclidean manner is whether the reasonably accurate performance found in Experiment 1 is maintained when the lengths to be compared are presented in 3-D. That is, can one compare length intervals in depth with length intervals in the frontoparallel plane? The results of Baird and Biersdorf (1967), Heine (1900), Loomis et al. (1992), and Thouless (1931) suggest that human observers may have difficulty performing this task. More specifically, if the scaling in the depth dimension is different than the scaling in the frontoparallel plane, observers may be unable to accurately compare 3-D lengths oriented in different arbitrary directions.

We designed the present experiment to clarify whether human observers have accurate knowledge of 3-D lengths in near visual space. The 3-D lengths were defined simultaneously by both motion and stereopsis. The task was similar to that of Experiment 1, namely, to identify which temporal interval contained the line segment that was longer in 3-D. Because the displays were shown in near visual space, we wanted to approximate natural viewing as closely as possible. The retinal images of objects presented in near visual space contain strong effects of perspective: Projected lengths on the retina vary not only as functions of physical lengths but also as functions of distance from the observer. If human observers can accurately perceive euclidean length, their responses must be invariant over the perspective changes associated with differences in viewing distance. Toward that end, we designed this experiment to compare the performance obtained when viewing distance was varied between the two temporal intervals of a single trial with that obtained when viewing distance was held constant during a trial. If performance for length discriminations is unimpaired across changes in viewing distance, this would be an additional source of evidence to indicate that the perception of length is euclidean.

Method

Observers. The observers were the same 3 observers who participated in Experiment 1.

Apparatus. The apparatus was identical to that used in Experiment 1, except for the addition of stereoscopic-viewing hardware. The stereoscopic half-images were presented using LCD (liquid crystal) shuttered glasses that were synchronized with the monitor's refresh rate. The left and right views of a stereo pair were displayed at the same position on the monitor screen, but they were temporally offset. The left and right lenses of the LCD glasses shuttered synchronously with the display so that each view of the stereo pair was seen only by the appropriate eye. The CRT was refreshed at 120 Hz; thus, each view of a stereoscopic half-image was updated at half that, or 60 Hz.

Stimulus displays. The stimulus patterns for this experiment were random wire-frame figures similar to those used by Wallach and O'Connell (1953) and Norman and Todd (1993). The task and experimental method was identical to that of Experiment 1. A two-alternative temporal forced-choice procedure was used along with the method of constant stimuli. The line segments whose 3-D lengths were to be compared across the two temporal intervals of a trial were solid, whereas all other line segments in the 3-D figures were dotted. All endpoints of the line segments were randomly distributed within a cubical volume with dimensions of 14 cm^3. The rotation axis was indicated by a thin, solid, vertical line segment, which was continuously displayed throughout the motion sequence. The rotation axis was displayed to ensure that the observers had a fixation target so that their convergence could be maintained at a specific distance during the trial. In addition, nonius markers were provided prior to the start of each temporal interval to ensure that the convergence was appropriate before as well as during the motion sequence. A stereoscopic example of a representative stimulus pattern is shown in Figure 2.

Two 3-D lengths (standard and test) embedded within different wire-frame figures were presented during each trial. The two lengths differed in their orientation in 3-D space. The actual physical viewing distance to the CRT monitor was 85.0 cm. The simulated viewing distance to the rotation axis of the 3-D figure varied across trials by a random amount up to 25.0 cm (i.e., from 60.0 cm to 110.0 cm from the observer). This viewing distance was either constant across the two temporal intervals of the same trial or variable over the 60.0–110.0-cm range. Whether the simulated viewing distance was held constant or was variable across the temporal intervals of a single trial was varied across separate experimental blocks, as was the magnitude of the two standard 3-D lengths. There were, therefore, four separate experimental conditions (2 × 2 factorial design). The two standard 3-D lengths, 6.0 cm and 9.0 cm, were the same as those used in Experiment 1. The test 3-D lengths either were shorter than the standard by 5%, 15%, 25%, or 35% or were longer than the standard by 5%, 15%, 25%, or 35%. There were 20 replications for each of these eight test lengths, producing 160 trials per block. Five experimental sessions of the four blocks were run for each observer. Therefore, 100 trials were obtained for all conditions. Each observer followed a different random order of the four blocks within any given session.

The apparent-motion sequence for each temporal interval consisted of 45 distinct frames, which were presented at 30 Hz. Therefore, a given temporal interval's duration was 1.5 s. The two intervals were separated by a 1.5-s blank pause. Each apparent-motion sequence specified the rotation of the wire-frame figure about a vertical axis. The angular extent of the rotation was always 20°, although the angular velocity was randomly varied for each display from possible values of 20.7, 25.0, 31.6, or 42.0 degrees per second. Thus, the displays could appear with varying numbers of oscillation cycles over the fixed 1.5-s presentation interval.

At any given position in an apparent-motion sequence, the observers saw a stereoscopic view of the stimulus pattern. The stereoscopic views for each observer were appropriate for their individual interpupillary distances. The wire-frame figures were presented at some location in depth, within 85.0 ± 25.0 cm from the observer. Whereas the actual distance to the monitor was always 85.0 cm, the simulated viewing distance was variable (i.e., the rotation axis was given a disparity relative to the monitor so that it was brought forward from or recessed behind the actual surface of the CRT). The room illumination was kept low so that

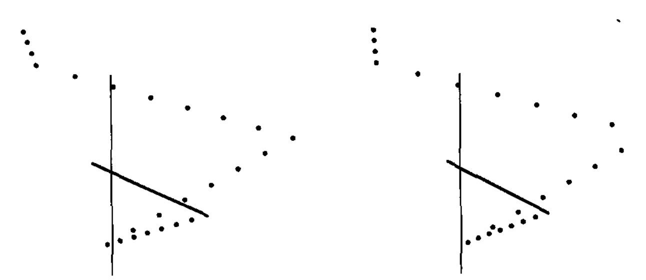

Figure 2. A stereoscopic example of a stimulus pattern used in Experiment 2. This stereogram was designed for cross-free fusion.

the stationary CRT surface was not visible. It is important to keep in mind that convergence markers were present both before and during the trial so observers could maintain appropriate convergence for the simulated viewing distance. In addition, the projections of the wire-frame figure were perspective, not orthographic. Because of the perspective projection, vertical disparities were also present within the optical patterns. Longuet-Higgins (1982) showed that vertical disparities provide information about absolute distance to an object and thus can scale the horizontal disparities. Together, horizontal and vertical disparities provide potential information to unambiguously specify depth intervals in stereoscopic vision. Thus, there were multiple simultaneous sources of information about viewing distance available in our patterns to provide scaling for the stereoscopic displays.

Two constraints were applied during the generation of these optical patterns. First, the 3-D length within any temporal interval (either the standard or the test length) had to have at least a 20° angle relative to the line of sight in the first frame. This was done to ensure that despite the random orientation of the lengths in 3-D, there was always a visible line segment within the projected image (i.e., the degenerate condition of a line projecting to a point in the image never occurred). Second, we ensured that at the beginning of the apparent-motion sequence for each temporal interval, the physically longer line segment in 3-D did not have a projected length that was longer than the actual length of the shorter line segment. This was accomplished by presenting the longer line in a suitable orientation relative to the observer, so that it was foreshortened to some degree. This constraint ensured that the task could not be performed solely by comparing the two 2-D lengths in the image. The effectiveness of this stimulus constraint is shown in Figure 3. This figure shows the results of a simulation where the response "longer presented first" or "longer presented second" was based on the mean 2-D lengths of the standard and test line segments across their apparent-motion sequences. The solid curves show that for both the constant and variable conditions, the "3-D" task could be performed with reasonable accuracy solely on the basis of 2-D length differences. This above-chance performance in the simulation was possible because lengths that are longer in 3-D are usually longer in 2-D projections as well. On any given trial, a 2-D strategy may fail because of other factors, but over time, a simple 2-D strategy leads to reasonable performance.

We wanted to force the observers to base their responses on the perceived 3-D lengths of the standard and test line segments. When the stimulus constraint described above was implemented in the simulation, the 2-D response strategy was no longer successful (see the dashed lines in Figure 3). In fact, adopting the 2-D strategy in this case would cause an observer to be incorrect, with his errors opposite to that of what would be appropriate. Figure 4 shows the results of an identical simulation, except the responses were based on the maximal 2-D image lengths across the apparent-motion sequences. The qualitative pattern of results of this simulation is identical to that of the previous simulation.

Procedure. The observers' task was to decide whether the longer line segment in 3-D was presented during either the first or the second temporal interval of each trial. Prior to the start of each block of 160 trials, the standard length was shown to the observer.

Before each trial, a stereoscopically presented nonius marker was displayed so the observer could converge appropriately for the viewing distance used for that trial. When the observer was satisfied with his convergence, he pressed a button on the workstation's mouse. The first interval was then displayed. During the 1.5-s interinterval pause, a second nonius marker was displayed so the observer could converge appropriately prior to the start of the second temporal interval.

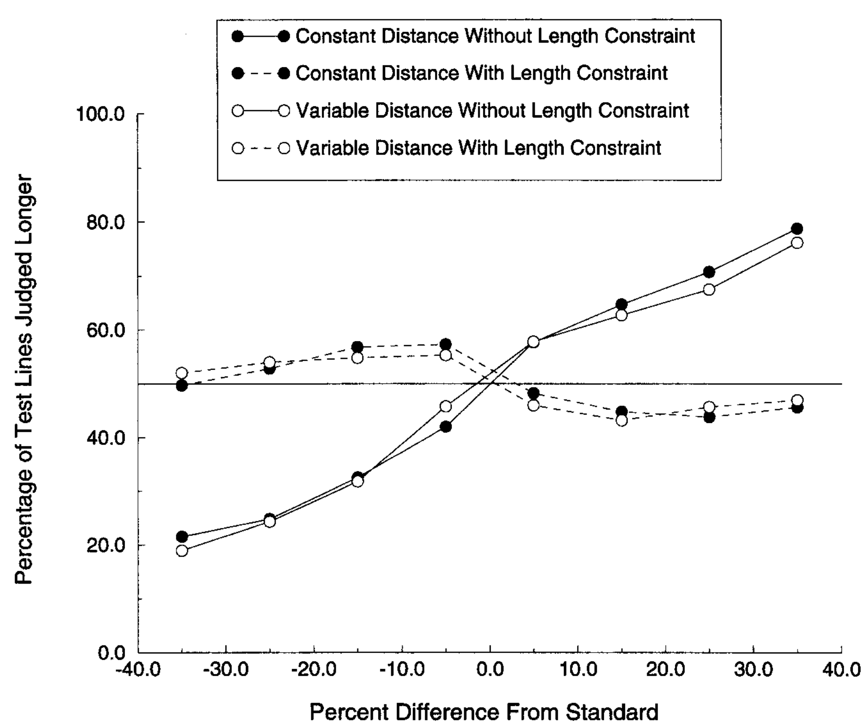

Figure 3. Results of the simulation where the responses were based on a simple strategy involving the mean projected two-dimensional lengths in the image. The standard line segment's three-dimensional length was 7.0 cm.

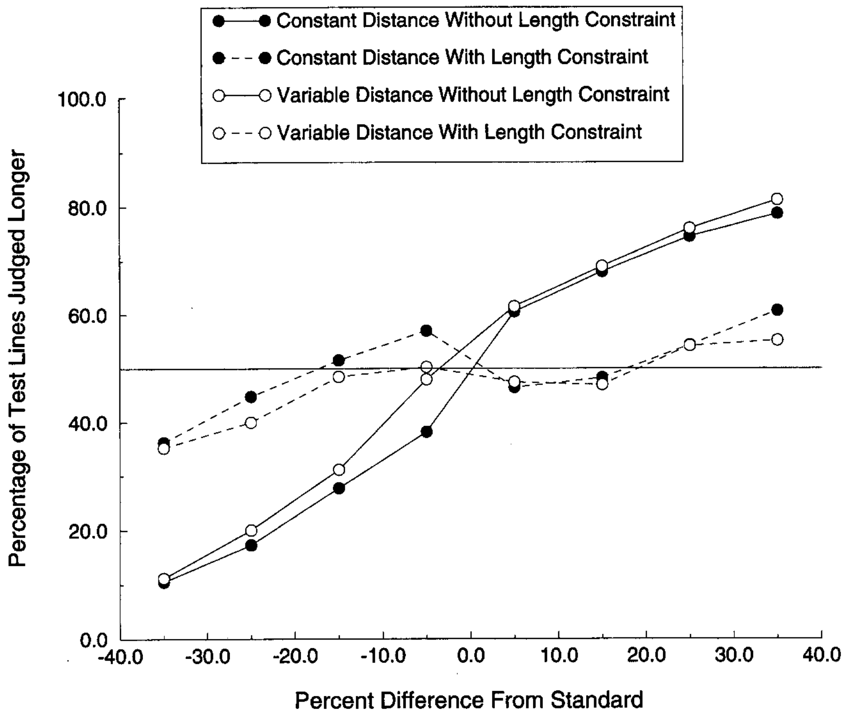

Figure 4. Results of the simulation where the responses were based on a simple strategy involving the maximum projected two-dimensional lengths in the image. The standard line segment's three-dimensional length was 7.0 cm.

The observer's response was recorded after the end of the second temporal interval. Auditory feedback (a short beep) was provided after each correct response.

Results and Discussion

The resulting psychometric functions for the individual observers are displayed in Figure 5. We combined the results for the 6.0-cm and 9.0-cm standard lengths because Weber's law was obeyed.

The thresholds for 3-D length discrimination when 2-D length differences were controlled for were much higher than those obtained for length discriminations in the frontoparallel plane. The Weber fractions for 2-D length discriminations obtained in Experiment 1 were approximately 3%. In the constant viewing distance–velocity condition in this experiment, they were about four times as high: 13.2%, 14.6%, and 11.1% for observers J.F.N., J.T.T., and V.J.P., respectively. Comparing 3-D lengths that have different orientations in space relative to the frontoparallel plane is evidently much more difficult than comparing lengths that have the same orientation. The Weber fractions for the variable viewing distance–velocity condition were about eight times as high as those obtained in Experiment 1. The individual thresholds for J.F.N., J.T.T., and V.J.P. were 26.3%, 24.4%, and 19.0%, respectively. As the observers went from the constant conditions to the variable conditions, their thresholds increased by 67.1% to 99.4%. Clearly, perception of 3-D length is not invariant over changes in viewing distance.

McKee, Levi, and Bowne (1990) found that for conditions resembling ours (display duration of 1,000 ms), Weber fractions for stereoscopic depth intervals were about 5.5%, whereas those for width discriminations in the frontoparallel plane were about half that, approximately 3.0%. The Weber fractions found in our experiment were higher for conditions using lengths with different 3-D orientations (about 13%) and were higher yet for conditions where distances to the two lengths were varied as well (about 23%). It would therefore appear that while discriminations of the disparity of depth intervals are worse than those of frontal intervals, as McKee et al. found, our high Weber fractions primarily reflect failures of constancy across variations in distance and orientation.

The results of this experiment seem to indicate that the perception of 3-D length does not exhibit constancy. Perceived length not only changes with physical length but also depends on distance and orientation relative to the observer. This failure of constancy occurred despite the fact that multiple simultaneous sources of information were available to redundantly specify the 3-D lengths. It is true that horizontal stereoscopic disparities are insufficient by themselves to specify absolute depth intervals (see Norman & Todd, 1992). However, we provided other information that could potentially scale the horizontal retinal disparities to recover veridical depth intervals. For example, nonius

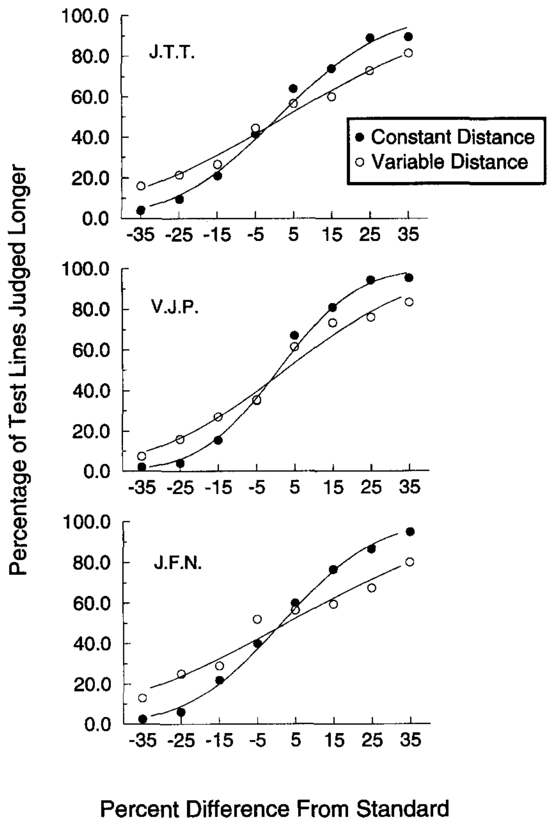

Figure 5. Individual psychometric functions from Experiment 2 for the 3 observers (represented by initials).

markers were displayed so the observers could converge appropriately for the simulated viewing distance before the start of each temporal interval. The rotation axis was continuously presented during each motion sequence so the observers could maintain that convergence. Our optical patterns also contained vertical disparities, which have been identified as a source of information that could theoretically lead to veridical perceptions of 3-D structure (Longuet-Higgins, 1982). Finally, the motion in our displays was sufficient by itself to veridically specify the 3-D lengths. Ullman (1979) and others have shown that euclidean geometrical properties, such as lengths, can be recovered from moving patterns if there exist at least three distinct orthographic views or two perspective views. The stimulus patterns used in this experiment contained motion as well as horizontal and vertical stereoscopic disparities. In addition, fixation markers were continuously provided to aid convergence. Nevertheless, our observers failed to demonstrate that they could perceive 3-D lengths in a manner consistent with euclidean axioms.

Although there were many potential sources of information available in these displays that in principle could have been used to determine the euclidean metric structure of the depicted objects, there was at least one other source of information that deserves to be noted, which, if relied on, could have potentially distorted their perceived 3-D structure. When an object is viewed in natural vision, its accommodative demand changes with viewing distance, but for the displays used in the present experiment, all of the lines had a fixed accommodative distance of 85 cm, regardless of the simulated distance used to generate the motions, disparities, and perspective in the pictorial displays. There are two aspects of this conflicting information that are important to highlight. First, because the absence of accommodative blur can occur only for objects that are flat (see Buckley & Frisby, 1993), the predicted effect of this conflicting information would be to reduce their perceived extension in depth. Second, because the effects of accommodation decrease rapidly with increasing viewing distance, we would expect to obtain the greatest reductions of perceived depth intervals for objects that are closest to the point of observation.

Experiment 3

We designed Experiment 3 to investigate whether the failures of depth constancy observed in Experiment 2 could be due to the conflicting information about the flatness of each display provided by the absence of accommodative blur. The strong prediction of that hypothesis is that other things being equal, the perceived length of a line segment in depth should increase with viewing distance as the flatness information provided by accommodation diminishes. An additional purpose of this experiment was to evaluate length discrimination performance for stereo and motion both separately and in combination. In particular, we wanted to determine whether these different sources of information have a facilitative effect on each other, so that the performance for the combined condition might be significantly better than would otherwise be possible for either stereo or motion presented individually (see Tittle & Braunstein, 1993).

Method

Observers. The three observers were the same as those who participated in Experiments 1 and 2.

Apparatus. The optical patterns were created and displayed on a Silicon Graphics Crimson VGXT workstation. In all other respects, the experimental apparatus was identical to that used in Experiment 2.

Stimulus displays. The stimuli were identical in almost all respects to those used in the variable viewing distance–angular velocity conditions in Experiment 2. Only two test lengths were used, 35% longer and 35% shorter than the standard length. A single standard length was used, 7.5 cm. The task was identical to that used in Experiments 1 and 2. There were three main conditions: stereo only, motion only, and stereo and motion combined. For each trial, the computer recorded not only whether the observers were correct in their judgments but also whether the temporal interval they selected as longer used the nearer or farther simulated viewing distance.

There were 20 replications of each of the two test lengths within any given experimental block of trials. The three stereo–motion conditions were run in separate blocks in a random order for each observer within a given experimental session. The observers participated in five sessions, providing 100 trials for each of the six combinations of test lengths and stereo–motion conditions.

Procedure. The observers' task and all other procedural details were identical to those of Experiment 2.

Results and Discussion

The results are shown in Figures 6 and 7. Figure 6 plots the percentage of trials in which the temporal interval with the nearer simulated viewing distance was judged by the observer to contain the longer line segment in 3-D. Because the simulated viewing distances were chosen at random within the same range for both the test and standard lengths, this measure should always be approximately 50% if constancy exists. In contrast, if significant distortions occur in near visual space that are specifically related to changes in viewing distance, large deviations from 50% may result. Johnston (1991) found that manipulations of viewing distance distorted observers' judgments of depth to height ratios of stereoscopically presented cylindrical surfaces. Tittle et al. (1995) also found stereoscopic judgments to be affected by viewing distance. In Figure 6, one can see that for all conditions, but especially for the stereo-only condition, the observers' judgments of length were significantly influenced by viewing distance. Given two lines with equal 3-D lengths, the observers would perceive the nearer one as longer. This result is consistent with the distortions found by Harway (1963), Thouless (1931), and others, who found that farther in-depth intervals in real-world environments appear more compressed (shorter) than closer ones. Note, however, that this is the opposite pattern of results from what would be expected if the displays had been perceptually distorted by the absence of accommodative blur, as suggested by Buckley and Frisby (1993).

The accuracy of the observers' judgments is indicated in Figure 7. The basic result replicated the results of Experiment 2. Even with large test differences from the standard (±35%), overall performance was relatively poor. Moreover, this performance did not seem to be affected by the

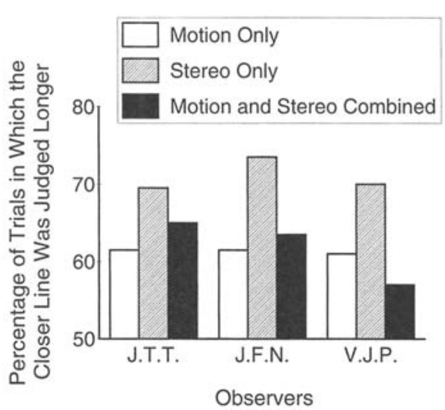

Figure 6. Constancy results from Experiment 3, examining how viewing distance (i.e., closer or farther in a two-temporal interval forced-choice trial) influences observers' discriminations of three-dimensional lengths.

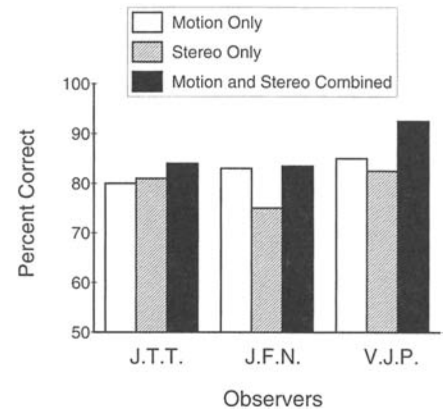

Figure 7. Discrimination accuracy results from Experiment 3.

combination of multiple sources of information. Performance was approximately equal for all conditions: motion only, stereo only, and motion and stereo combined. There was no systematic effect that would indicate a facilitation in performance for this task when multiple sources were combined.

Experiment 4

Experiments 1–3 used computer-generated optical patterns to evaluate observers' sensitivity to 3-D lengths based upon binocular disparity and motion. Under those conditions, observers failed to correctly perceive 3-D lengths. Although binocular disparities and motions are commonly thought to be the most important optical sources of information about 3-D form, it is possible that there is some extra source of information normally available in natural environments that could potentially lead to veridical perceptions of 3-D length. These nonpictorial sources of information could include gradients of accommodative blur (Buckley & Frisby, 1993) or the presence of an intervening ground surface to provide additional information about egocentric distance to more accurately scale binocular disparities. To investigate this possibility, we designed this experiment to test observers' perceptions of 3-D lengths between real-world objects viewed directly in near visual space (i.e., less than 2 m).

Method

Observers. There were 6 observers. Four of the observers were the authors, and 2 other observers were naive regarding the purpose of the experiment.

Apparatus. A Silicon Graphics Personal Iris (4D/25 TG) workstation controlled a set of 24 red LEDs that were arranged on a 180-cm × 90-cm table. A specially constructed electronic interface connected to the workstation's Centronics parallel port was used to turn the LEDs on and off.

Stimulus displays. The 24 LEDs were arranged in a pattern, as shown in Figure 8. A photograph of the apparatus is shown in Figure 9. The LEDs were turned on or off in pairs. There were 42 different pairs of LEDs. There were 11 length intervals oriented

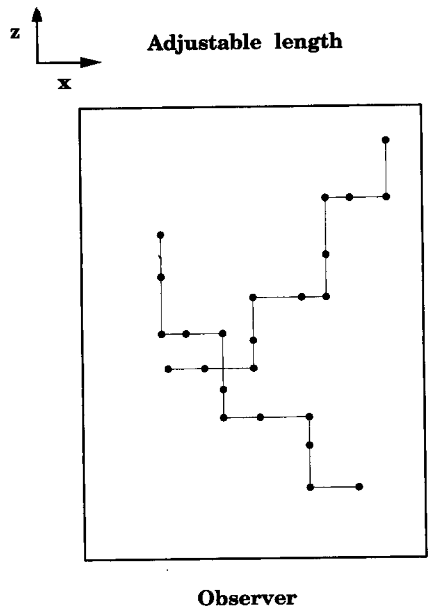

Figure 8. A schematic illustration of a top view of the arrangement of the 24 LEDs on the tabletop. The positions of the observer and the CRT where the adjustable length line was presented are indicated at the bottom and the top, respectively.

horizontally in the frontoparallel plane, 11 length intervals oriented in depth, and 20 intervals in an oblique orientation in depth, which had both frontoparallel and in-depth length components. Each LED was mounted 30 cm above the tabletop and was approximately 15 cm below the eye height of an average seated observer. The LEDs were placed on a smooth textured surface. The surface was a patterned sheet that was rumpled, forming a convoluted curved surface. The sheet covered and occluded all view of the hardware used to securely fasten the LEDs to the table. When turned on, an individual LED appeared to be a small red spot sitting on the textured surface.

Procedure. The observers' task on any given trial was to view a pair of LEDs and then to adjust the length of a 2-D obliquely oriented line on the Silicon Graphics monitor until its length matched that of the perceived interval between the two LEDs. When satisfied with the match, the observer pressed a button to record the response and to initiate the next trial. The monitor was located 195 cm from the observer, on the opposite side of the table upon which the LEDs were mounted. The observers were instructed that they could move their heads (and generate motion parallax) if they wished, as long as they remained seated.

In any given experimental session, matching adjustments were collected twice for each of the 42 length intervals defined by the LEDs. Each observer participated in five sessions, thus producing 10 matching adjustments for each of the 42 real-world lengths.

Results and Discussion

The first issue to be addressed is that of reliability. That is, for a given observer and a given physical length interval, how consistent were the 10 adjustments? The reliability for a given length interval (i.e., a single pair of LEDs) is expressed as the standard deviation of the adjustments relative to the mean (as a percentage). The 11 individual reliabilities for the horizontal intervals were then averaged to produce an overall reliability estimate. Overall reliability measures were similarly calculated for the 11 in-depth intervals and for the 20 oblique intervals. Table 1 shows these overall reliability estimates calculated for each observer for the horizontal, in-depth, and oblique intervals. It is evident that the observers were reasonably reliable over time in making these matching adjustments: The reliabilities ranged from 5% to 10%. But what about accuracy? We evaluated accuracy by calculating root-mean-square (RMS) errors. These errors show how much the observers' adjustments varied from the correct values. We calculated the RMS errors with the following equation, using the observers' 10 adjusted lengths for each of the 42 actual physical length intervals:

$$\text{RMS error} = \frac{\sum_{i=1}^{42}\sum_{j=1}^{10} \dfrac{\sqrt{(\text{adjusted}-\text{actual})^2}}{\text{actual}}}{10 \times 42}. \tag{1}$$

These RMS errors are shown in Table 2 as a percentage of actual length. If observers correctly perceive 3-D lengths except for random fluctuations, then for any particular interval, the RMS error should be equal to the reliability. However, if observers' perceptions are consistently distorted, then the RMS errors should be high relative to the reliabilities. In this case, it is evident from a comparison of Tables 1 and 2 that although the observers might have been reliable, they were not accurate. Thus, we concluded that there are systematic distortions involving the perception of 3-D lengths even in natural viewing situations.

The nature of this distortion can be illustrated by examining how frontoparallel intervals are perceived at varying viewing distances as compared with in-depth intervals. Figure 10 plots the adjusted lengths as proportions of the actual lengths at different viewing distances for both horizontal and in-depth intervals (oblique intervals are not represented in this plot). A value of 1.0 indicates that the mean of the observer's 10 length adjustments equaled the actual physical length interval between a pair of LEDs. If perceived

Figure 9. A photograph of the apparatus used in Experiment 4.

Table 1
Reliability of Observers' Matches Across Repeated Adjustments

Observer	Interval		
	Horizontal	Oblique	In-depth
J.F.N.	6.6	5.4	8.1
J.T.T.	7.5	6.4	6.9
V.J.P.	6.9	6.6	6.7
J.S.T.	6.6	6.7	7.4
H.F.N.	5.1	7.0	5.7
F.P.	7.7	10.6	9.7

Note. Each reliability was measured by the standard deviation of the adjustments for a single condition as a percentage of its mean.

space were euclidean in nature, the horizontal and in-depth values would be equal and would not vary with viewing distance. As can be clearly seen in Figure 10, however, this does not appear to be the case. The horizontal and in-depth intervals were perceived differently as the viewing distance was increased. Frontoparallel intervals were perceived to increase in size as they were presented at farther distances. In contrast, the adjusted lengths for the in-depth intervals decreased sharply as viewing distance increased, on average by 25% per meter. This means that equal-length intervals in depth become perceptually smaller the farther away they are presented. In other words, perceived space is increasingly compressed in depth at farther distances. This compression is similar to the distortion found with the computer-generated displays in Experiment 3 and with the distortions reported by Johnston (1991) and Tittle et al. (1995). Similar decreases in perceived in-depth intervals with increasing distance in real-world viewing have also been reported by Baird and Biersdorf (1967), Harway (1963), Loomis et al. (1992), and Thouless (1931). Pearson R correlation coefficients for the in-depth results shown in Figure 10 were calculated for all observers and were as follows: −.91 for J.F.N., −.84 for J.T.T., −.77 for V.J.P., −.75 for J.S.T., −.74 for H.F.N., and −.78 for F.P. The high negative correlations show that this decrease in apparent length with increasing viewing distance was significant.

The results shown in Figure 10 indicate that frontoparallel intervals were perceived differently than in-depth intervals and that the relationship between the two changed as a function of viewing distance. The observers' perceived space was anisotropically distorted so that distances in different directions were scaled unequally. The viewing distance where the two regression lines cross in each panel of Figure 10 represents the single distance for each observer for which perceived space was isotropic, that is, where equal-length physical lines presented horizontally and in-depth also appeared perceptually identical. At all other viewing distances, this was not the case. This special viewing distance was located between 50 cm and 85 cm for all of the observers, approximately at arm's length. This result is reminiscent of Helmholtz's apparent frontoparallel plane, where a physically planar surface appears planar and noncurved at only one viewing distance, which differs for different observers. Heine (1900) also reported that equilateral triangles in depth appear equilateral only when presented within 33–50 cm from an observer.

Until this point, we have been considering the perceived lengths in an extrinsic way: Are the lengths perceived veridically with reference to some external standard? However, we can also investigate the geometry of visual space in an intrinsic manner. For example, consider a triangle on a flat planar surface. Its three angles sum to 180°. One can also draw a triangle between three points on a sphere, connecting the points with the shortest possible curves. One can readily determine that the space on which this figure lies is intrinsically curved because the angles now add to more than 180°. Furthermore, the deviation from 180° grows larger as the size of the triangle is increased.

It is possible for us to evaluate the intrinsic structure of near visual space because of the specific spatial arrangement of the LEDs that we used. Within the pattern of LEDs, there were 10 sets of overlapping right triangles (20 total triangles, 10 big and 10 little); one set is illustrated schematically in Figure 11. Each observer estimated the sides of 20 triangles. Since 6 observers participated in the experiment, we obtained judgments for 120 total triangles. We took the mean of the observers' judgments for each side of the triangles as the best estimate of the perceived length. For 103 of the 120 triangles, the adjusted hypotenuse was less than the square root of the sum of the other two sides ($p <$ .00001, two-tailed sign test). This finding seems to imply that the perceived space of the observers was elliptic or positively curved (Rucker, 1977, p. 34). However, this relationship between the length of the hypotenuse and the other two sides is true only for a right triangle. Although our triangles were right triangles in physical space, we do not have any direct evidence that they were right triangles perceptually.

We performed an additional geometrical analysis of the data, one that did not assume anything about the specific shape of the triangles. For this analysis, it was important that the big and little triangles overlapped spatially and that they shared a common vertex (indicated by the small square in Figure 11). Remember that for each observer, we obtained estimates for all three sides of the 10 sets of big and little triangles. For the moment, let's assume that perceived space is euclidean, that human observers' knowledge of

Table 2
Root-Mean-Square Errors of Observers' Matching Adjustments as Calculated by Equation 1

Observer	Interval		
	Horizontal	Oblique	In-depth
J.F.N.	13.5	24.6	25.1
J.T.T.	10.5	19.3	19.4
V.J.P.	10.0	21.4	20.0
J.S.T.	23.4	31.6	34.3
H.F.N.	21.0	33.5	32.2
F.P.	23.7	39.7	37.6

Note. These root-mean-square errors indicate how much the observers' adjustments varied from the correct values, as a percentage of the correct value.

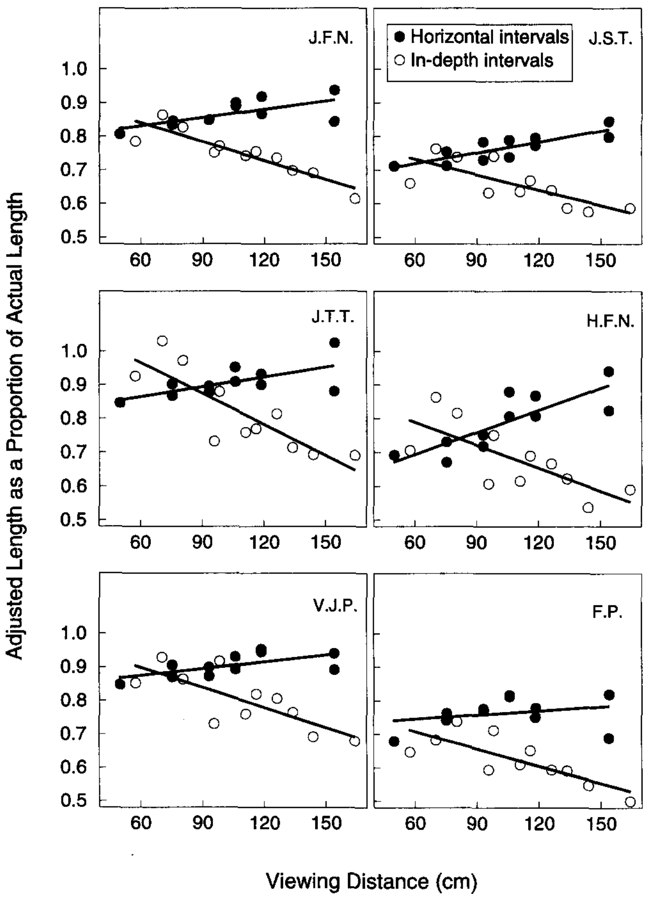

Figure 10. Plot of adjusted versus actual length ratios as a function of viewing distance for both frontoparallel and in-depth intervals for the 3 observers (represented by initials). A ratio of 1.0 indicates perfect matching performance.

spatial layout is not distorted. If this assumption is true, (a) we can calculate an angle for that shared vertex by using the law of cosines, given the perceived lengths of each triangle's sides, and (b) the angles calculated from the big and little triangles for a given shared vertex must be equal (within measurement error). If those two angles differ significantly, however, then perceived space cannot be euclidean. In particular, in a noneuclidean geometry, the angle at a shared vertex of two differently sized triangles will have different values for each size. The difference between the angles for the two figures will increase as the space becomes more curved. In our experiment, each of the 6 observers judged the sides of 10 sets of triangles, so we had a total of 60 calculated angles for both the big and little triangles. In 48 of those sets of triangles, the angle calculated for the big triangle was less than the angle calculated for the little triangle. The probability of this occurring by chance alone is less than .00001, as assessed by a two-tailed sign test. Our results, therefore, show that visual space is noneuclidean: The direction of the errors indicates that the geometry of visual space is elliptic, which is in agreement with the previous analysis. The average calculated angles for the big and little triangles are shown separately for each observer in Table 3. Most stereoscopic studies examining the structure of perceived space have found it to be hyperbolic, or negatively curved. All of these investigations used sets of luminous points in the dark, with no visible surroundings. In natural visual situations, however, it has been reported that some observers' perceptual space is elliptic (Battro, Netto, & Rozestraten, 1976).

General Discussion

The results of the current experiments show that the perception of length can be very accurate in certain contexts but is not accurate in general. Weber fractions for perceived length ranged from 2–3% for parallel lengths in the frontoparallel plane to 25–30% for 3-D lengths presented at different positions and orientations. Failures of length constancy were found as the viewing distance was varied, both for the computer-generated lengths and for length intervals in the real world. Converging evidence from multiple experiments (as well as results from other researchers) indicates that perceived intervals in depth become systematically compressed with increasing viewing distance, whereas perceived intervals in the frontoparallel plane increase slightly or remain relatively constant with increasing viewing distance. This general pattern of results provides strong evidence that the relationship between physical and perceived space cannot be described as a euclidean mapping.

The results from Experiment 4 provide additional evidence that the intrinsic structure of perceptual space may be noneuclidean as well. Previous experiments using stereoscopic stimuli in reduced-cue conditions have usually found perceived space to be hyperbolic, or negatively curved (for a review, see Foley, 1980; see also Blank, 1961; Foley,

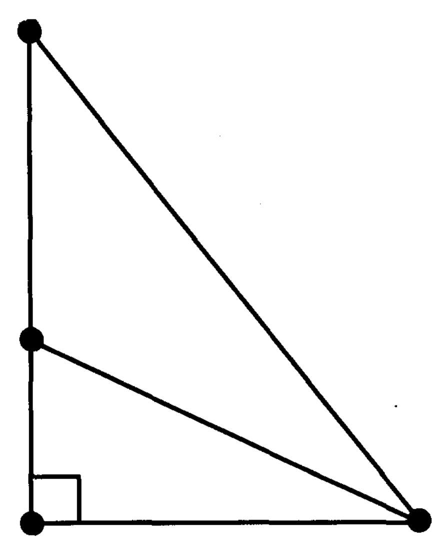

Figure 11. A schematic illustration of 1 of the 10 sets of overlapping big and little triangles defined by the 24 LEDs. Note that the big and little triangles share two vertices—the right-angle vertex is marked by a small square.

Table 3
Mean Calculated Angles (in Degrees) From the Law of Cosines for the Vertex Shared by the Big and Little Triangles Given the Observers' Length Adjustments

Observer	Big triangle angle	Little triangle angle
J.F.N.	80.1	83.4
J.T.T.	82.2	85.3
V.J.P.	75.2	84.0
J.S.T.	81.6	89.0
H.F.N.	78.0	82.4
F.P.	71.0	76.0

Note. If perceived space is euclidean, then the big triangle angle = little triangle angle = 90.0°.

1972; Zajaczkowska, 1956), although there is other evidence to suggest that its structure may be elliptic, at least for some observers, under more natural full-cue conditions (Battro et al., 1976). This latter conclusion is also supported by the results of the present experiments.

It is important to keep in mind that in all of our experiments, there were ample amounts of optical information sufficient for observers to accurately perceive length. The observers failed to take advantage of this information, even when the lengths were redundantly specified by many simultaneous sources of information. In Experiment 4, for example, observers had all of the normal sources of optical information available in natural environments: binocular disparities (horizontal and vertical), motion parallax, shading, texture gradients, convergence, accommodative blur, and so forth. The perceptual distortions reported over the last century persist during natural viewing in near visual space in full-cue conditions.

If there are perceptual failures of length constancy, why don't we notice this when we move about in the real world? If a given physical length at 10 m is perceived to be shorter than the same length presented at 1 m, or 50 cm, why doesn't the length appear to distort as an observer walks toward it? Why don't the lengths of objects appear to shrink and distort as we move about and view them from different orientations? The most plausible reason that is compatible with our phenomenal impression of environmental solidity is that euclidean geometrical properties, such as lengths, do not form the primary basis of our perceptual representations of object shape. Instead, we believe that the perceived invariance of the environment is a direct result of the visual system's use of more abstract geometrical properties that remain invariant over the distorted mapping between physical and perceived space.

For any given type of perceptual distortion, there will always be some aspects of an object's structure that will be unaffected. Suppose, for example, that physical and perceived space were related by an affine transformation, as has been suggested in certain contexts by Norman and Todd (1992, 1993), Todd and Bressan (1990), and Todd and Norman (1991). This type of perceptual mapping would systematically distort euclidean properties, such that equal-length lines in different orientations could appear perceptually to be unequal, but there are numerous other properties that would remain invariant, such as the relative lengths of parallel line segments or the planarity of a surface. Thus, even if there were systematic errors in perceived relative length for line segments oriented in different directions, it might still be possible to accurately judge the relative lengths of parallel line segments (e.g., see Lappin & Fuqua, 1983; Purdy & Gibson, 1955) or to accurately discriminate the presence or the absence of surface curvature (e.g., see Norman & Lappin, 1992; Todd & Bressan, 1990). There is a considerable amount of evidence from the present experiments and from the earlier results of Baird and Biersdorf (1967), Loomis et al. (1992), and Tittle et al. (1995) that both affine and euclidean properties are systematically distorted in near visual space under full-cue conditions. There is other evidence to suggest, however, that the mapping between physical and perceived space is approximately affine at relatively long viewing distances beyond 20 m (see Harway, 1963; Wagner, 1985).

Although the increasing compression of perceived intervals in depth with viewing distance in near visual space does not preserve the euclidean or affine properties of objects in the environment, it does preserve other aspects of 3-D structure that could potentially form the basis of our perceptual representations. Consider, for example, the ordinal arrangements of objects in depth. Any nonhomogeneous stretching transformation along the line of sight would systematically alter the relative depth intervals among objects at different viewing distances, but it would have no effect whatsoever on their relative depth orders. That is to say, with this particular type of geometric distortion between physical and perceived space, an observer could be highly accurate at judging whether one object is farther away in depth than another, even though it might not be possible to accurately judge the specific depth interval by which they are separated. Information about ordinal structure can come in a variety of forms (see Todd & Reichel, 1989). For example, although observers may be surprisingly inaccurate and unreliable at judging depth intervals from binocular disparity (McKee et al., 1990; Tittle et al., 1995), they can accurately detect the relative depth order of visible features from disparity differences of just a few seconds of arc (Westheimer & McKee, 1978, 1979, 1980). Similarly, there are other aspects of optical stimulation, such as partial occlusions, that provide no information at all about the metrical structure of objects in the environment, yet they can precisely specify how they are ordered in depth.

Another important property that would remain invariant over any continuous mapping between physical and perceived space is the topology by which the edges and the vertices of visible objects are connected to one another. Thus, if a pair of edges in physical space are connected at a common vertex, they should appear perceptually to be connected as well. It is interesting to note in this context that one of the most successful theories of object recognition, recently proposed by Biederman (1987), relies exclusively on affine, ordinal, and topological properties for the perceptual representation of 3-D structure. According to this account, objects are represented using a small set of volumetric primitives, called *geons*, which are defined by the cotermination of edges at vertices (a topological property); the ordering of those edges with respect to one another (an ordinal property); and whether they are straight, curved, or locally parallel (affine properties). Although this model uses no information about metrical structure, it is remarkably successful at recognizing objects, even over variations of size and orientation.

Biederman's (1987) model is instructive, we believe, because it demonstrates clearly that complex perceptual judgments about an object's shape could potentially be achieved without having to represent its euclidean metric structure. It is obvious from our day-to-day experiences that human observers can accurately perform a wide variety of visually guided activities, but there have been few theoretical analyses to determine the minimal amounts of information from which these activities could be successfully accomplished. In the psychophysical investigation of 3-D form perception, observers typically do well on tasks that could potentially be performed on the basis of affine, ordinal, or topological properties, but they usually have great difficulty on tasks that require an explicit knowledge of euclidean structure (i.e., a comparison of length intervals in different positions or orientations).

Why would the visual system not incorporate the precision of euclidean geometry for perceptually representing the 3-D layout of objects in the environment? We suspect the answer may be that euclidean analyses are more computationally complex and are less robust to changes in viewing conditions than are analyses based on affine, ordinal, or topological properties. A sensible strategy for any visual system would be to compute only those properties that are needed to perform required tasks. Although observers can make judgments of euclidean properties if they are required to do so, there is a growing amount of evidence that suggests that our knowledge of these properties is surprisingly crude and imprecise. Given the perceived stability of objects as they move relative to an observer, it is likely that euclidean properties are at best a minor component of our perceptual representations of 3-D form.

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