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Optimal spatial localization is limited by contrast sensitivity

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Abstract

Bisection is one of several spatial localization tasks that achieve hyperacuity performance levels. We find that optimal bisection thresholds, and hyperacuity tasks in general, are no better than might be expected from simple contrast detection and discrimination performance. The three-line bisection task can be described in terms of the test-pedestal paradigm where the test pattern is a horizontal dipole and the pedestal is a horizontal three-line pattern with equal spacing between the lines. When the dipole test is added to the center line, the line shifts up or down, depending on the test polarity. For low contrast pedestal lines at the optimal separation, the bisection threshold falls between the observer's own dipole contrast detection threshold and the bottom of the dipole contrast discrimination dipper function. At higher pedestal strengths performance degrades with a slope of about 0.5–0.7, similar to that found in contrast discrimination tasks. Therefore, bisection performance is compatible with expectations based on contrast discrimination data. At large pedestal line separations (> 10 min) bisection thresholds in min are about 1/60 the separation and relatively independent of pedestal strength. These findings are consistent with the idea that two processes are involved in limiting bisection performance; the first limit is based on contrast sensitivity of the system and the second limit to performance is based on a local sign or position tag processing. Finally, when bisection is compared with Vernier acuity and blur resolution tasks, where the test is also a dipole, bisection performance falls roughly midway, better than Vernier acuity but worse than blur resolution.

Keywords: Hyperacuity; Test-pedestal; Bisection

1. Introduction

Estimating the midpoint of two closely spaced lines is one of many tasks that fall into the category known as a visual hyperacuity. Hyperacuity tasks are those for which spatial localization thresholds are less than the diameter of a receptor (Westheimer, 1975). The world record for line bisection was set by Dr Dennis Levi in 1984 with a localization threshold of 0.85 arc s (Klein & Levi, 1985; McFarlan, McWhirter, McCarthy & Young, 1991). The level of performance associated with hyperacuity tasks has inspired the development of computational models of the phenomena. While progress has been impressive (Carlson & Klopfenstein, 1984; Klein & Levi, 1985; Wilson, 1986) threshold prediction based on physiologically plausible mechanisms requires numerous assumptions about bandwidth, sensitivity and density. In recent years we have approached the problem of hyperacuity by considering the stimulus in terms of the test versus pedestal intensity framework (Hu, Klein & Carney, 1993; Beard, Klein & Carney, 1997; Carney & Klein, 1997). This approach has enabled us to predict thresholds for individuals on tasks such as blur discrimination, Vernier acuity and contrast discrimination based on their own multipole detection thresholds without resorting to assumptions about underlying mechanisms (Klein, Casson & Carney, 1990; Carney & Klein, 1997).

The typical bisection stimulus consists of three parallel lines. The bisection threshold is the distance the center line must be displaced from the true bisection point for lack of symmetry to be detected. Optimal displacement thresholds for this type of stimulus are about 2–3 arc s (Wang & Levi, 1994). Three-line bisection thresholds can be viewed in terms of the strength of a test stimulus which, when added to a pedestal, results in a detectable lack of symmetry or displacement. The pedestal in this case is the three

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target lines and the test is a dipole which when added to the center line shifts it slightly up or down. This is depicted graphically in Fig. 1. The question we pose is, can an individual's bisection threshold be predicted from their dipole detection threshold? Previous data on spatial localization tasks for large line separations indicate the answer is no when the task is in the wide separation, local sign regime (Morgan & Ward, 1985; Burbeck & Yap, 1990; Wang & Levi, 1994). However, when the pedestal lines are close together, performance is consistent with the use of local contrast sensitive mechanisms (Klein & Levi, 1985; Wilson, 1986; Wang & Levi, 1994). By using the test-pedestal approach it is possible to measure contrast sensitivity for the test and directly compare it with bisection performance for a range of line separations.

2. Methods

2.1. Subjects

Three observers participated in the experiments, an author and two volunteers naive as to the goals of the experiment. All observers had normal or corrected to normal visual acuity of 20/20 or better.

2.2. Stimuli

The three-line bisection targets were generated with a Neuro-Scientific Venus pattern generator and presented on a Tektronix 608 display scope with a horizontal display raster and a 107 cd/m^2 mean background luminance. Each pixel of the 256 × 256 pixel display subtended 0.33 min when viewed from 4 m. The display was viewed binocularly. The stimuli were oriented horizontally and extended across the width of the display.

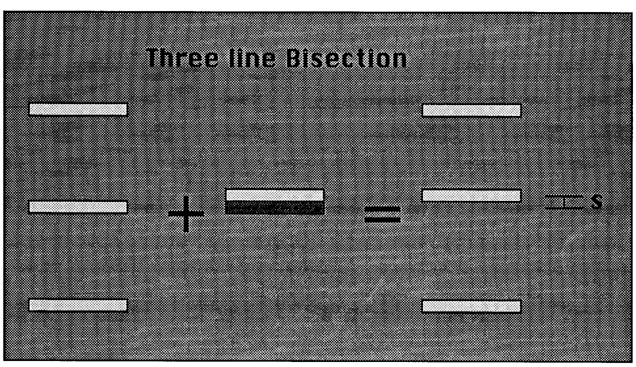

Fig. 1. The three-line bisection task can be viewed as detection of a dipole test stimulus added to the middle of three equally spaced lines. Thresholds can be expressed as either the magnitude of spatial displacement of the center line in s arc (or two outside lines) or the added dipole strength in %min^2 required to produce an equal displacement.

The lines were 1.41° long and 0.66 min (two pixels) wide. Sub-pixel displacement of the center line was achieved by shifting the centroid of the two pixel wide line using gray scale intensity adjustments of the adjacent pixels (Morgan & Aiba, 1985).

To evaluate bisection performance in terms of the test-pedestal paradigm we make use of the class of stimuli known as multipoles. Line and dipole multipoles are identified by their order, 0 and 1, respectively (Klein, 1989; Carney & Klein, 1997). Each successive multipole of higher order is the derivative of the preceding multipole. It can be constructed from a negative and a positive of the preceding or lower order multipole. For example, a line is simply two edges of opposite polarity placed near each other. Similarly a dipole is two adjacent lines of opposite polarity. The strength or moment of each multipole is also related to the moment of its lower order multipole. While the strength of a stimulus is commonly referred to as its contrast, it is an incomplete description for localized targets. Strength should include stimulus size as well as intensity. The strength of a line (%min) is simply the contrast of the line ($\Delta L/L_{\text{background}}$) times the separation in minutes of the two edges comprising the line (the line width). As the separation becomes vanishingly small so does the line strength. The moment of a dipole is the moment of the two opposite polarity lines it is composed of, times their separation in minutes, hence the units, %min^2. Here again as the separation becomes vanishingly small so does the dipole strength; the opposite polarity lines cancel. These definitions of multipole strengths are in agreement with how multipoles are defined in electrostatics (Jackson, 1962). The use of these measures of multipole strength requires that the width of each multipole, except for the edge, be smaller than the line spread function of the eye. Since our stimuli were two display pixels wide (0.66 min) they were sufficiently narrow for accurate measurement of stimulus strength.

Using these definitions of multipole strength, the three-line bisection task can be described in terms of the test-pedestal framework. The pedestal is the center line to which the test is added. The displacement of the center line is accomplished by adding a dipole test to the center line of the pedestal as shown in Fig. 1. The relationship between dipole strength and displacement magnitude is the same as previously described for line Vernier acuity tasks where a dipole added to half the length of a line displaces that half of the line (Klein et al., 1990; Carney & Klein, 1997). The magnitude of the test dipole for a given center line displacement in this bisection task is given as,

$$M_{\text{d}}\ (\%\text{min}^2) = \text{displacement (min)} * M_l\ (\%\text{min}) \qquad (1)$$

where M_{d} is the dipole moment and M_{l} is the line pedestal moment. This relationship is used to convert bisection thresholds expressed in min into dipole test strengths. When performance is measured for a range of pedestal line strengths the data can be presented as a test versus pedestal strength (TVS) curve, where threshold test strength (dipole) is plotted as a function of pedestal strength (line). This function is analogous to the TVC curves presented in studies of contrast discrimination sensitivity (Legge & Foley, 1980).

2.3. Procedure

Each stimulus presentation lasted 2 s. The self-paced rating-scale method of constant stimuli with 3–5 levels of test strength was used to determine the 84% correct hit rate and 50% correct false alarm rate ($d' = 1$) for detection or discrimination thresholds (Levi & Klein, 1982). Data analysis was performed using the signal detection analysis program, ROCFLEX (Klein & Levi, 1985). Each threshold was based on data from three or more runs, with 100–125 stimulus presentations per run. After each stimulus presentation and response, auditory feedback provided the observer with the correct identity of the stimulus condition. Observers were encouraged to take a few practice trials at the beginning of each run. During a run, a trial could be discarded (before making a response) if a distraction disrupted the normal gathering of data.

2.4. Line and dipole detection thresholds

Multipole detection thresholds were determined for line and dipole targets. Four stimulus strengths were usually employed: approx. 0, 0.8, 1.2 and 1.6 times the estimated detection threshold. The levels were chosen such that the d' between each level was about 0.7 with a transducer exponent of 1.5.

2.5. Three-line bisection thresholds

The onset and offset of the entire three-line stimulus were synchronous and abrupt. Bisection thresholds were determined for a range of line (pedestal) strengths and separations. The base separation between three lines ranged from 1.3 to 60.0 min. The lines comprising the bisection stimulus ranged in strength from about 3–200 %min.

Bisection thresholds for each pedestal line separation and strength were determined in separate runs with three to five runs per condition. We used the method of constant stimuli with the center bisection line in one of five equally spaced positions, two above the bisection point, at the bisection point and two below the bisection point. The center line spatial offsets were about -2, -1, 0, 1, 2 times the bisection threshold (positive and negative indicate upward and downward shifts of the center line) for each particular condition as determined in preliminary runs.

Table 1
Line and dipole detection thresholds, with standard errors, for the three observers

Observer	Line (%min)	Dipole (%min^2)
TJ	2.08 ± 0.17	1.82 ± 0.08
TC	3.56 ± 0.14	2.43 ± 0.09
ME	3.63 ± 0.35	3.89 ± 0.18

3. Results

The line and dipole detection thresholds ($d' = 1$) are shown in Table 1 along with standard errors (including between run variability) for the three observers. Observer TJ had significantly lower thresholds for both stimuli, which probably accounts for that observer's superior performance on the bisection results described below.

In Fig. 2, each subject's bisection threshold for the multiple line separations are expressed as a spatial displacement in seconds, as a function of the line pedestal strength. Thresholds decrease with increasing line strength. Optimal conditions for detecting an offset are high strength lines with approximately 2–5 min line separations. The lowest thresholds were 3, 4 and 2 s for observers TC, ME and TJ, respectively. At high line strengths and separations greater than 10 min, thresholds are about 1/60 of the line separation.

In Fig. 3, the data in Fig. 2 are replotted with thresholds now expressed in terms of the test dipole strength as a function of the pedestal strength. For example, if pedestal strength is 100 %min and threshold is 3 s (0.05 min) then threshold in dipole units is 100 %min times 0.05 min or 5 %min^2. The TVS curves of Fig. 3 are analogous to the more familiar TVC curves for contrast discrimination tasks (Legge & Foley, 1980). Also plotted in each panel is the observer's dipole detection threshold as indicated by an arrow along the y-axis. At low contrasts and close spacing, the thresholds are slightly lower than the individual observer's own dipole detection threshold. At high line strengths thresholds increase with a slope of about 0.5–0.7. In general, these TVS functions for small line separations are similar in shape to contrast discrimination data, even a weak dipper shaped function is evident. For line separations greater than about 10 min, thresholds are well above the dipole detection threshold. The differences between the large and small line separation data sets indicate that at least two processes may be involved in the bisection task.

One of the advantages of describing performance in the test-pedestal framework is that it is often possible to compare thresholds in dissimilar tasks that share the same test stimulus. We have previously reported TVS curves for Vernier acuity, blur resolution and contrast

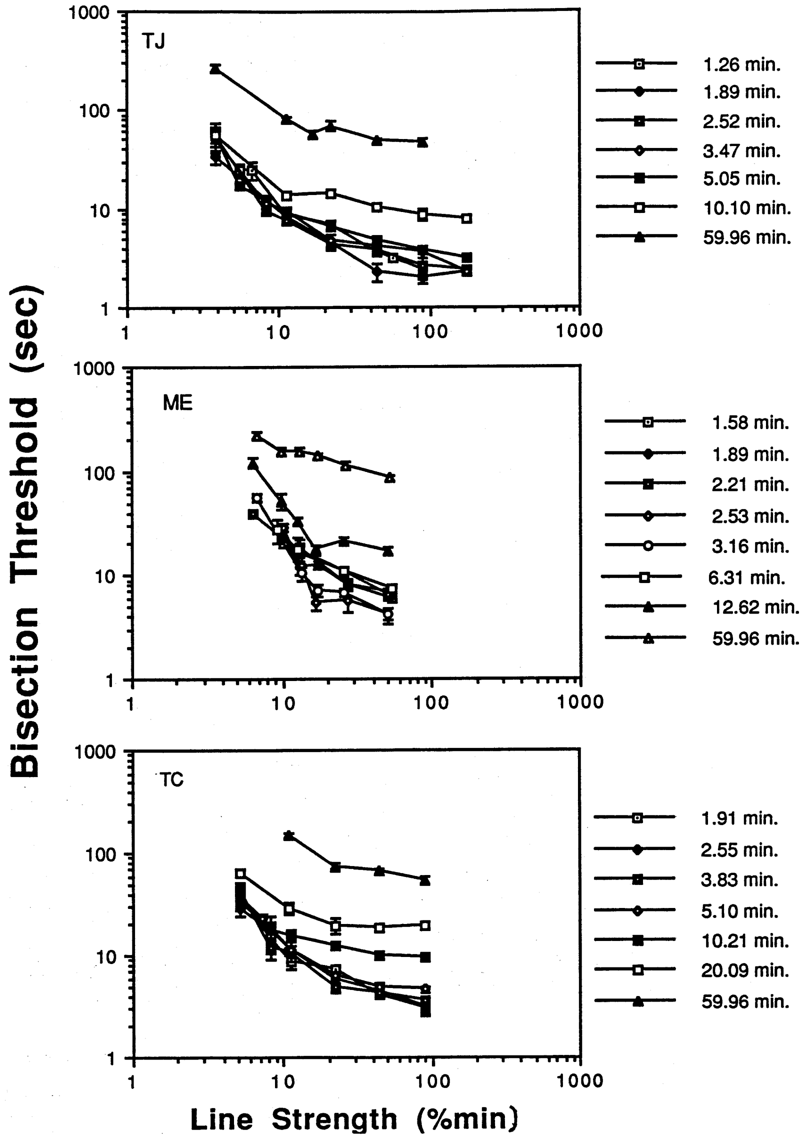

Fig. 2. Three-line bisection thresholds expressed as a center line displacement in seconds for three observers with a range of line separations, 1.26–59.96 min. Thresholds decrease with increasing line strength. For line separation, greater than about 6 min, thresholds increase rapidly with increasing line separation. The optimal thresholds are about 2, 4, and 3 s for observers TJ, ME and TC, respectively.

discrimination tasks where the test stimulus was a dipole in each case (Carney & Klein, 1997). In Fig. 4, the performance for two observers in the bisection task is compared to their own line Vernier acuity, dipole contrast discrimination (JND) and edge blur threshold data which was collected using the same experimental procedures. In each panel, bisection thresholds are plotted for two line separations (open and filled squares), separations that roughly bracket the range where separation had little differential effect on threshold. This is also the range that achieves the lowest thresholds. Since the units of pedestal strength differed across the four tasks, the pedestal strength for each task was expressed in contrast threshold units (ctu) in which thresholds are normalized by their pedestal detection threshold. The pedestals were edge, line and dipole for the edge blur, Vernier and bisection acuity, and JND tasks, respectively (see figure 7 from Carney and Klein (1997), the source of some of the data). The dipole test detection threshold for each observer is indicated as an arrow along the ordinate of the graph.

In all four tasks, thresholds increase with pedestal strength for strengths above about five to ten times detection threshold. At lower pedestal strengths we often observe a flat region and an increase in threshold for very low pedestal strengths which probably reflects limited overall stimulus visibility. The line bisection thresholds (open and closed squares) fall below the Vernier acuity thresholds (open diamonds) and above the edge blur (open triangles) and JND (open circles)

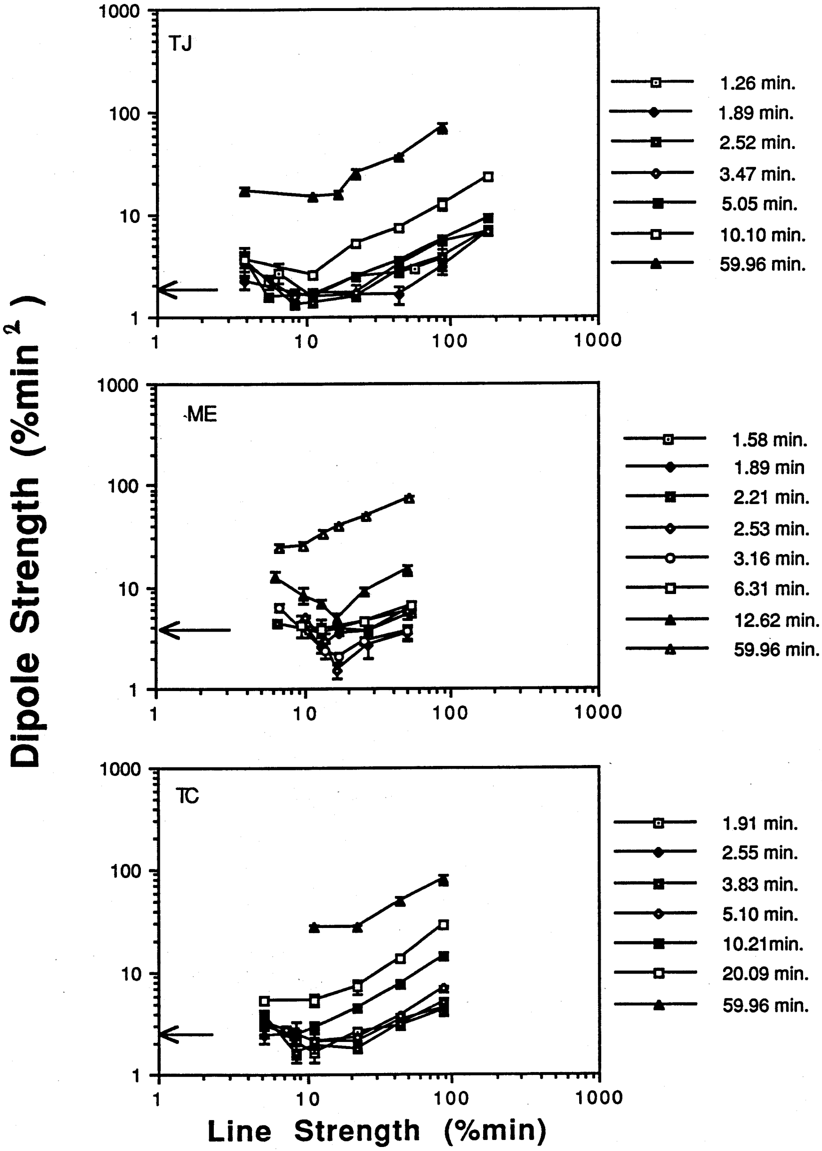

Fig. 3. Three-line bisection thresholds in Fig. 2 have been transformed so that threshold is now expressed as the added test dipole strength in %min^2. These threshold versus strength (TVS) functions are similar in shape to contrast discrimination functions. Thresholds increase with pedestal strength at the higher pedestal strengths. At the low to medium pedestal strengths, thresholds are relatively flat with an occasional upturn at the lowest pedestal strengths, giving the dipper shape function associated with contrast discrimination data. For line separations greater than about 6 min, thresholds rapidly increase with increasing separation. When bisection thresholds are expressed in dipole units we can also indicate the dipole detection threshold on a uniform field, shown by arrows along the abscissa. The best three-line bisection thresholds for each subject generally fall between their own dipole detection threshold and the bottom of the contrast discrimination dipper function.

thresholds. The lowest bisection thresholds can be predicted, within about 50%, based on an observer's own dipole detection threshold and the bottom of the JND function. The lowest bisection thresholds fall somewhere between those two points.

3.1. Five-line bisection task; a new world record

While increasing line separation can elevate bisection thresholds, adding additional flanking lines can decrease bisection thresholds. Using a five-line bisection stimulus, Klein and Levi (1985) have reported a bisection threshold of 0.85 s (75% correct). In fact the subject, Dr Dennis M. Levi, is listed in the Guinness Book of Records for having the world's best visual acuity, based on this bisection threshold (McFarlan et al., 1991). Our observer TJ had rather low thresholds on the three-line bisection task so we decided to examine his five-line bisection performance. The five line bisection stimulus was similar to that used by Klein and Levi (1985). The viewing distance was 4.4 m for a pixel size of 0.29 min. The background luminance level was reduced to 20 cd/m^2 and the line contrast was 1070%. Each line was two pixels wide. In Fig. 5 the thresholds

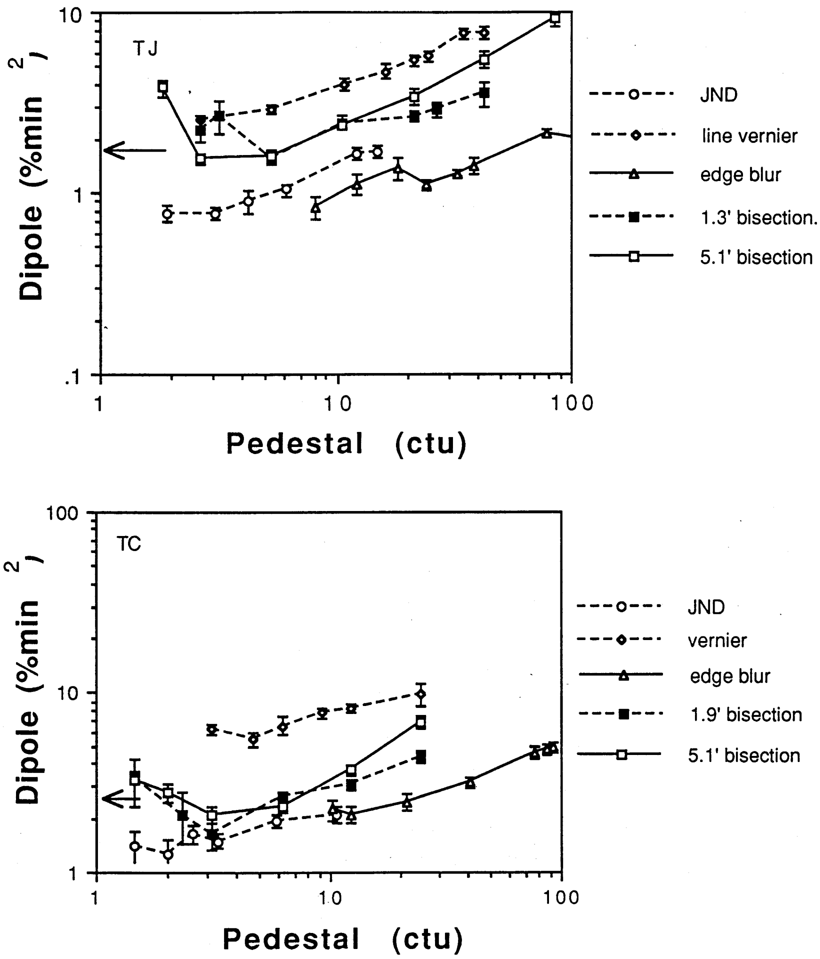

Fig. 4. By expressing thresholds in dipole units we are able to compare performance across different spatial tasks. In the four tasks, line Vernier acuity (open diamonds), three-line bisection (open and filled squares), contrast discrimination (open circles) and edge blur (open triangles), the test is a dipole. Only the pedestal differs across the four tasks. To avoid cluttering the graphs, bisection data are shown for the 1.3 (1.9) and 5.1 min separations, which bracket the separations with the lowest thresholds. The arrow along the ordinate indicates the observer's dipole detection threshold on a blank screen of the same mean luminance. Since pedestal strengths are in different units, each is normalized by its own detection threshold to achieve the common units, contrast threshold units (ctu). Data are presented for two subjects; the third subject's data were not plotted because that bisection data set was restricted to less than ten times the pedestal threshold. The Vernier acuity thresholds are the highest, which probably reflects the use of a non-optimal orientation cue (Carney & Klein, 1997). The JND and edge blur tasks have the lowest thresholds and have similar shaped curves, with the edge blur curve shifted to larger pedestal strengths (less masking). This shift of the dipper region is likely related to the similarity in spatial frequency content between test and pedestal with JND being most similar so facilitation occurs at lower pedestal strengths. The bisection threshold curves fall about midway between the Vernier acuity and JND thresholds.

for subject TJ on a five-line bisection task for a total of 14 runs are plotted along with the original bisection world record data. Subject TJ can reliably (75% correct) discriminate a 0.57 s displacement in this five-line bisection task which sets a new world record[1]. Under similar experimental conditions, except using a three-line bisection stimulus, this subject's threshold was 1.16 s (75% correct), twice that obtained with the five-line stimulus.

[1] We have presented thresholds in customary units of seconds to enable comparison with past data. However, in our opinion performance is based on the contrast sensitivity of the underlying mechanisms and is not really a spatial localization task.

This difference might be understood in terms of the visual system's localized luminance integration. The two additional flanking lines effectively elevate the mean luminance locally for the mechanisms participating in the bisection task. This may produce a more uniform luminance environment for the mechanisms detecting the difference between pedestal and pedestal plus test. The optical blurring of the closely spaced lines may effectively remove most of the line pedestal's masking effect.

In order to calculate the effective background luminance we modeled the blurring of the equally spaced lines of the stimulus using a rectangular blur function of 1.45 min in width. After applying this blur function we are left with a constant luminance bar of width

(5*1.45) 7.25 min (Klein, 1994). Now shifting the center line by the bisection threshold distance produces 0.57 s wide white and black lines. The luminance of the white line is twice that of the local surrounding luminance so its contrast is about 100% as is the dark line. The light and dark lines are located 0.725 min above and below the midpoint of the five-line stimulus. These two narrow lines approximate a dipole. The strength of this dipole is the strength of the two narrow lines times their separation or 1.38 %min^2 (0.57/60min*100%)*1.45 min = 1.38 %min^2 dipole strength). This threshold dipole strength is based on 75% correct performance which corresponds to a $d' = 0.67$. At $d' = 1.0$ the threshold is expected to be 1.38/0.67 = 2.06 %min^2. The dipole detection threshold on a uniform field for subject TJ (Table 1) at $d' = 1.0$ was 1.82 %min^2, close to the dipole threshold value calculated for the five-line bisection stimulus assuming a local luminance gain control mechanism. Thus, it seems that with the two flanking lines in the five-line bisection task we have created a local platform of sufficient width to constitute a region of uniformly elevated mean luminance. The pedestal has effectively been removed so masking is eliminated. For the three-line stimulus there seems to be a factor of two masking effect.[2]

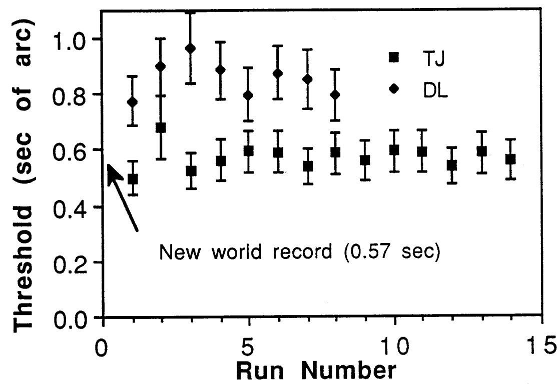

Fig. 5. Five-line bisection thresholds and standard errors in seconds of arc are plotted for 14 consecutive individual runs of 125 trials each for subject TJ. Also plotted are the world record bisection thresholds for eight runs of subject DL from Klein and Levi (1985). Our subject, TJ, consistently has a lower bisection threshold. TJ's mean threshold was 0.57 s as compared to the old record of 0.85 s (these thresholds are at the 75% correct level ($d' = 0.67$) rather than 84%, for comparison with previous results).

4. Discussion

The test-pedestal approach has been applied to spatial localization tasks to determine if performance is better than might be expected based on contrast sensitivity alone. In the specific case of three-line bisection acuity the task can be described as detection of a test dipole added to the center pedestal line of a three-line stimulus. Bisection acuity is one of several hyperacuity tasks which, when viewed from the test-pedestal perspective, is found to be compatible with predictions based on the observer's own contrast sensitivity for the test, combined with mechanism masking at high pedestal strengths. When plotted as a TVS function at optimal line separations, optimum performance falls between the observer's dipole detection threshold and the bottom of the dipole contrast discrimination function. At line separations greater than about 10 min, optimal performance is about 1/60 of the line separation. At pedestal strengths above about ten times threshold, performance deteriorates with a slope of about 0.5–0.7 on a plot of log-threshold versus log-pedestal contrast.

4.1. Comparison with other visual tasks having the same test stimulus

The presentation of threshold data as a TVS function offers several advantages. It enables us to determine if performance on hyperacuity tasks that historically seem to indicate some special capability of the visual system, is any better than one might expect based on the contrast sensitivity of the visual system. For the bisection task, at optimal separations, we see that thresholds are consistent with detection threshold for the test alone. Although the spatial localization capacity of the visual system is impressive, performance does not require any special mechanisms beyond those that account for contrast sensitivity. In fact, bisection performance was slightly worse than contrast discrimination thresholds for the same test stimulus (see Fig. 4). By presenting thresholds in terms of dipole test strength, we are able to compare performance across different tasks that have the same test stimulus. For example, Fig. 4 shows that edge blur thresholds are lower than three-line bisection thresholds. Such a comparison would not be as meaningful if we were just to report thresholds in strictly spatial units. It would not be clear how the edge blur and bisection offset are related.

[2] When performing the five-line bisection task one has the feeling that at threshold a dark line is being discriminated. The luminance profile of the stimulus, with the center-line shifted by the threshold amount and after gaussian blur, contains four dark lines. One of the lines is darker than the rest because of the center line shift. Threshold might be based on the discrimination of this darkest line from the other lines rather than discrimination of the test dipole. A 0.57 s threshold shift results in a line strength of about 0.95 % min (0.57s/60*100%). The line threshold for this subject at a higher mean luminance was 2.08%min (Table 1). The factor of two difference may be because this discrimination task is in the dipper (facilitation) region of the discrimination function.

4.2. Bisection threshold ambiguity of a factor of two

Throughout this paper we have treated the pedestal as the center line to which the test is added to achieve a certain center-line displacement. In the case of the three-line bisection stimulus, the pedestal component is ambiguous. We could think of the pedestal as the three lines with test dipoles being added to one of the outside lines. This approach would double all the bisection thresholds shown in Figs. 3 and 4 relative to the JND and blur thresholds (the Vernier acuity task has a similar pedestal ambiguity problem) (Klein et al., 1990). A more detailed discussion of these issues is provided in Carney and Klein (1997).

Furthermore, if we assume the pedestal includes all three lines we have the complication that pedestal strength, in terms of visibility, would depend not only on the individual line contrasts and widths but also on their separation. In the extreme (not explored in this paper), three abutting narrow lines would have three times the strength of each individual line. This would shift the bisection data horizontally in Figs. 3 and 4 by up to a factor of about three, depending on the line separation. To be consistent with our earlier use of multipoles in the test-pedestal framework (Carney & Klein, 1997) we are treating the single center line as the pedestal. This simplifies plotting bisection data with different line separations on the same figure and facilitates comparison with other tasks such as Vernier acuity and resolution. The decision to use a single line definition of pedestal only effects pedestal strength when the lines are closely spaced (<3 min), except for probability summation for detecting one versus three lines at large separation.

4.3. Modeling performance

Bisection performance is predicted reasonably well by a simple algorithm. An observer's bisection threshold in dipole units for any given pedestal (line) strength is the greater of (1) the observer's dipole detection threshold; (2) dipole detection threshold * (pedestal strength/(10*line detection threshold))$^{0.5}$; or (3) line separation * pedestal strength/60. This formulation captures the idea that three floors limit performance. The first limit is contrast sensitivity given here by the observer's dipole detection threshold. A reasonable alternative for the first limit might be the bottom of the observer's contrast discrimination function or perhaps halfway between the detection and discrimination thresholds. Some bisection thresholds do fall below the dipole detection threshold but they are never lower than the bottom of the JND function. The second limit (important for closely spaced lines) is based on contrast masking by the pedestal with a slope of 0.5. The factor 10 in the second limit forces this limit to intersect the first

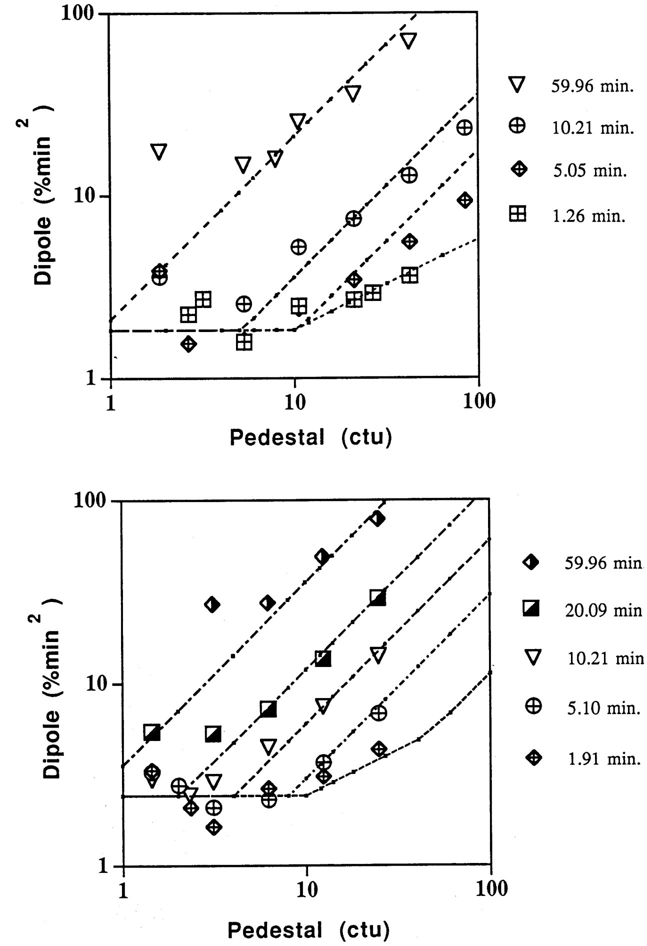

Fig. 6. The symbols indicate the bisection thresholds for subjects TJ and TC. The dashed lines are the model predictions based on the three performance floors described in the text. Except for some low pedestal strength conditions, the experimental data is well fit by the model.

limit at ten times the pedestal detection threshold. These two floors are operative for separations less than about 10 min and presumably reflect the sensitivities and profiles of early spatial filters. The third floor, which is important at larger separations, reveals a fundamental spatial uncertainly of the visual system, which has become known as the local sign hypothesis (Levi & Klein, 1990). In Fig. 6, the data for subjects TC and TJ are plotted along with the predictions based on the formulation described above.

Predictions and data are similar for all but the lowest pedestal strengths. For the small line separations performance is worse than predicted, which we suspect is due to limited visibility of the pedestal at a couple times detection threshold. The poor performance at large separations and low pedestal strength may be due to an error in estimating the visibility of the outer reference lines. We normalized the data by the detection threshold of a foveated line. Our estimate of line strength (in ctu) may be an overestimate since at large separations the lines are in the periphery where detection threshold increases (Levi, Klein & Wang, 1994).

4.4. Summary

The accurate spatial localization achieved in various visual hyperacuity tasks has intrigued researchers for a long time. Using the test-pedestal paradigm, we have been able to compare performance on four tasks, bisection, Vernier acuity, edge blur and contrast detection-discrimination. The test pattern for each task was the same, a dipole. Dipole contrast detection and discrimination results establish the sensitivity of observers to the test pattern. When combined with appropriate pedestal patterns, the spatial localization performance under optimal conditions for bisection, edge blur (resolution) and Vernier acuity, were no better than one might expect from the observer's own contrast sensitivity for the test itself. While visual hyperacuities remain impressive, it now seems that mechanisms no more complicated than those associated with contrast detection and discrimination need be involved. What remains is to explain why performance is slightly worse than what might be expected from contrast discrimination.

Acknowledgements

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