Perception & Psychophysics
1994, 56 (6), 681-690

Size scaling and its effect on letter detection

PAULA GOOLKASIAN
University of North Carolina, Charlotte, North Carolina

Two ways of scaling letter size across eccentricity were investigated in a choice reaction time (CRT) task. Experiments 1 and 2 tested cortical magnification theory (M-scaling), while Experiment 3 used scaled sizes drawn from Anstis's regression formula (A-scaling). Experiment 4 compared both scaling techniques, together with the effect of exposure duration and the absolute size of the foveal letter. Results showed that scaling effectiveness improved when large rather than small foveal letters were used. A-scaling with a large foveal letter provided a good fit for the data at parafoveal locations, but underestimated the letter sizes needed at large eccentricities. M-scaling with a large foveal letter size produced CRTs that were independent of eccentricity. Exposure duration did not substantially affect performance.

This investigation explores the effect of size scaling on letters presented at varied eccentricities, from 0° to 15° of visual angle. It is well known that visual performance declines when stimuli appear at nonfoveal retinal locations. From the fovea to 10° eccentricity, visual acuity declines by a factor of three in parallel with the decline in cone density. For larger eccentricities, the decline is steeper and assumed to reflect ganglion cell density (Fiorentini & Berardi, 1991). Stimulus size is often scaled to compensate for the changes in resolution across the visual field and to maintain visibility. According to the cortical magnification theory of peripheral vision (Virsu, Näsänen, & Osmoviita, 1987; Virsu & Rovamo, 1979), stimuli presented at varied retinal locations can have equivalent visibility if their cortical representations are equivalent. The values that are used to scale the stimuli are in inverse proportion to the striate cortical magnification factor. This technique, referred to as *M-scaling*, indicates the length in millimeters along the striate cortex that corresponds to a degree of visual angle. Although M-scaling has been studied primarily with threshold tasks, this study tested the application of M-scaling to a choice reaction time (CRT) task with letters as stimuli.

M-scaling has been found to be effective in a variety of studies (Bijl, Koenderink, & Kappers, 1992; Kitterle, 1986; Levi, Klein, & Aitsebaomo, 1985; Virsu et al., 1987). In general, the findings indicate that, compared with the processing of constant-sized (N-scaled) stimuli, processing of scaled stimuli shows a minimal effect of presentation location. However, considerable task differences are reported. Kitterle (1986) reports that M-scaling equates visibility in brightness and color discriminations, but for spatial tasks such as vernier thresholds, phase discriminations, and detection of sinusoidal gratings, performance is better with foveal than with peripheral stimuli. Virsu et al. (1987) tested the application of cortical magnification theory to seven visual tasks and found a slight foveal superiority in every one of them. Moreover, foveal/peripheral processing differences were found to increase slowly with eccentricity. The foveal superiority was attributed to an inaccuracy in the scaling formula and also to a scaling failure. There may be qualitative differences in foveal and peripheral processing such that compensating for size differences in cortical projection is insufficient to overcome processing differences that occur across retinal location.

Evidence for such an interpretation comes from a study by Strasburger, Harvey, and Rentschler (1991). They measured contrast thresholds for the detection of numbers presented at varied locations from 0° to 16° of eccentricity and found that increasing stimulus size did not fully compensate for the inferiority of peripheral vision compared with foveal vision. Their data were in agreement with the cortical magnification factor up to 6° of eccentricity but for greater eccentricities the stimuli needed to be larger. A close inspection of their scaling function, however, shows that size scaling was based on a small foveal size [.07° (as displayed by the solid line in Figure 9, p. 504)]. Although this size was recognizable at a foveal location, it may have underestimated the sizes needed for peripheral viewing. Levi et al. (1985) suggest that it is not the specific value chosen for the foveal M that is important, but rather, the relative change in M with eccentricity. For example, the stimulus size at 10° needs to be about 4 times its foveal size.

However, it is possible that with high-level processing (i.e., number or letter detection), M-scaling may be effective only for suprathreshold stimulus sizes. Unfortunately, there is not much research on M-scaling with a

---

This work was supported in part by funds from the Foundation of The University of North Carolina at Charlotte and from the State of North Carolina. Thanks are due Lester Krueger for his help with writing this manuscript and to Lauren Goodman, Linda Howell, J. Derek Hyde, and Karl Lehnhardt for their help with data collection. Requests for reprints should be sent to Paula Goolkasian, Department of Psychology, UNCC, Charlotte, NC 28223 (e-mail: fpy00pag@unccvm.uncc.edu).

letter-detection task. A study that is cited with some frequency, however, is that by Anstis (1974), in which recognition thresholds for letters were found to increase linearly with eccentricity to 30°. Anstis developed a chart which displays the increase in letter size needed to maintain visibility at specific eccentricities. When compared with M-scaling, Anstis scaling (*A-scaling*) is similar in that some constant change in letter size is required with eccentricity, but the regression function identified by Anstis uses a smaller slope. Also, Whitaker, Makela, Rovamo, and Latham (1992) have recently reported that although performance across retinal locations was equated by a change of scale, there were enormous differences in the rate at which performance declined with eccentricity across tasks.

The present research looked at the effectiveness of size scaling in maintaining visibility in a CRT task with letters. Visual performance can be measured in a variety of ways and CRT tasks differ from threshold studies in that the former involve a judgmental process in which the stimulus must be labeled as well as recognized (Smith, 1968). Size scaling would be expected to affect perceptual recognition in the same way in the CRT task as it does in threshold studies. However, there is also a fundamental difference in stimulus characteristics such that in threshold studies, minimal stimulus information is presented for a long duration, while in CRT studies, a much stronger stimulus appears for a brief duration.

The question with which the present study was concerned was whether size scaling would equate visibility as effectively with CRT as it had with threshold data. Since a much stronger stimulus is used, it is relatively unknown what effect size scaling would have on letter visibility. Research with suprathreshold stimuli has shown rather constant visual performance over a range of stimulus sizes. For example, Farell and Pelli (1993) showed that when numbers and letters are presented with small and large sizes mixed in a display, subjects' accuracy at target identification was unaffected by the mixed display; but accuracy of locating the target was higher in a single than in a mixed-scale display. These findings suggest that even though stimulus size does not affect RTs, there is some evidence that visual attention is tuned to scale and that requiring subjects to attend to more than one stimulus size may impair performance. Cave and Kosslyn (1989) compared RTs to stimuli of varied sizes and found that they increased with disparity between actual and expected stimulus size. Such an effect would be apparent in this study when subjects are responding to stimuli scaled according to cortical magnification theory, with slower RTs to scaled stimuli than to constant-sized stimuli across retinal location.

Two ways of scaling letter size were studied. Experiments 1 and 2 used M-scaling, while A-scaling was used in Experiment 3; the two were directly compared in Experiment 4. These scaling methods were similar in that letter size increased with eccentricity, but they differed in the amount of change. A-scaling used a much smaller slope, so that size changes were more gradual. It was of interest to compare the effectiveness of the scaling methods and to determine whether with one or both of these methods CRT would be independent of eccentricity.

The effect of the absolute size of the foveal stimulus was also studied by scaling with small and large letters. Table 1 presents the sizes of the stimuli used in each of the scaling techniques. The small sizes were chosen to be near threshold at the foveal location, while the large ones were chosen to be suprathreshold. (These sizes were arbitrarily determined from pilot testing with briefly presented letters.) If the relative size of the stimuli is the essential factor in equating visibility across eccentricity, as some suggest (e.g., Levi et al., 1985), the absolute size of the stimulus should not be found to interact with retinal location; large and small letters would be processed in similar ways across retinal location. Conversely, an interaction would suggest that letter size is an important variable in CRT tasks.

Consistent with CRT tasks, exposure durations for the stimulus letters were brief. In all conditions, the exposure durations were long enough for subjects to clearly process the letter, but were shorter than the 180–250 msec needed to initiate an eye movement (Alpern, 1971; Saslow, 1967). In addition, a mask followed the offset of the stimulus to erase any stimulus-persistence effects and to control the amount of time that the stimulus was available for processing. With this procedure, it was possible to study differences in processing across eccentricity. It has been suggested that the rate of processing information is slower in the periphery than in the fovea (Eriksen & Schultz, 1979). Letters were presented for either 16 or 50 msec in Experiments 1, 2, and 3, and for 25, 50, and 75 msec in Experiment 4. If the subjects were not able to complete stimulus processing at any of the durations tested, an interaction of exposure duration with retinal location would be obtained. Exposure duration was not otherwise expected to have much of an effect on performance.

Table 1
Letter Size (Heights in Degree of Visual Angle) as a Function of Retinal Location for Each of the Experiments

	Retinal Location (degrees)			
Size	0°	5°	10°	15°
	M-Scaled			
Small				
Experiments 1 and 4	.34	.92	1.50	2.11
Experiment 2	.47	1.27	2.06	2.90
Large				
Experiment 4	.74	2.00	3.26	4.57
	N-Scaled			
Experiments 1 and 2	1.14	1.14	1.14	1.14
	A-Scaled			
Small				
Experiments 3 and 4	.34	.47	.61	.74
Large				
Experiments 3 and 4	.74	.88	1.02	1.14

EXPERIMENTS 1 AND 2

The first two studies tested M-scaling and its effect on CRT. Values of M were taken from Virsu and Rovamo (1979) and were used to scale letters presented at locations from 0° to 15° to the right or left of fixation. At each retinal location, the M-scaled stimulus was compared with a constant-sized (N-scaled) stimulus. The purpose of M-scaling was to equate cortical size across retinal location, while the N-scaled stimuli were used to equate retinal distance. If scaling the size of the letters was sufficient to equate visibility across the visual field, letter-detection RTs and error rates should not be affected by presentation location. If, however, retinal location effects were found in spite of the use of scaled stimuli, this would suggest a scaling failure and would be consistent with studies which found that compensating for the resolution differences may not be sufficient to overcome foveal/peripheral processing differences (Strasburger et al., 1991; Virsu et al., 1987). Also of interest was the degree to which RTs would be affected by presenting mixed-sized stimuli to subjects. Longer RTs to scaled stimuli compared with those to constant-sized stimuli would support the notion that visual attention is tuned to stimulus scale. Experiments 1 and 2 were similar, except that in Experiment 2, a slightly larger foveal stimulus was used for scaling. Both studies compared scaled stimuli with constant-sized stimuli at each of four retinal locations, with two exposure durations, 16 and 50 msec.

Method

Subjects. The subjects (28 in Experiment 1 and 23 in Experiment 2) were men and women from the University of North Carolina at Charlotte. They all reported normal (or corrected-to-normal) vision and no history of eye impairment, and participated to obtain credit points in a psychology class. Subjects in the four experiments were volunteers from the same subject pool, but different students participated in each experiment.

Stimulus materials. The stimulus was an upper-case letter, either *K* or *D*, produced from the Macintosh character set (Geneva font). These letters were chosen because they are highly discriminable, and would not be as likely as some other letters to produce findings that would be dependent upon specific letter properties. Only two letters were used because it was necessary to keep variability to stimulus items at a minimum in order to isolate the effects of the manipulated variables. The stimulus letter was printed in black against a bright background with a luminance of 121 cd/m^2. The stimulus was always black, with a luminance of 24.30 cd/m^2. (Luminance was measured with a Minolta luminance meter LS 100.)

The stimulus letter was presented at one of seven locations on the screen—0°, 5°, 10°, or 15° to the right or left of the fixation point. Eccentricities were measured to the midpoint of the letter. Letter sizes were scaled such that the letter's width was always half the letter's height. Scale values were derived from the following formula (Virsu & Rovamo, 1979): $M = 7.99(1 + .33E + 0.00007E^3)$, where M is the reciprocal of the underlying cortical magnification factor and E is eccentricity in degree of visual angle. The values of M calculated for the four retinal locations tested in this experiment, in order of increasing eccentricity, were .125, .338, .546, and .776. These values provided the relative proportions needed to increase the peripheral letter heights relative to the foveal letter heights. Foveal letter heights were arbitrarily selected from the results of pilot testing with briefly presented letters. The peripheral letters were scaled in proportion to the value of M. As a consequence, at 5°, the letter heights were 2.7 times the foveal letter size; at 10°, they were 4.4 times the foveal value; and at 15°, they were 6.2 times the foveal letter height. In Experiment 1, the letter size for the scaled letter was 5 points at 0°, and at retinal locations 5°, 10°, and 15°, the letter sizes were increased, respectively, to 14, 22, and 31 points. With the subject seated 30 cm from the screen, the visual angles subtended by the letter heights were, respectively, .34°, .92°, 1.50°, and 2.11°. In comparison, the N-scaled letter was 17 points and it subtended a visual angle of 1.14°. In Experiment 2, while the N-scaled letter was the same size as it was in Experiment 1, the sizes of the scaled letters were as follows: At 0°, the letter size was 7 points and at retinal locations 5°, 10°, and 15°, the letter sizes were increased, respectively, to 19, 30, and 45 points. The visual angles subtended by the letter heights were, respectively, .47°, 1.27°, 2.06°, and 2.9°.

The stimuli were displayed on an Apple color high-resolution RGB 13-in. monitor. The monitor used a P22 phosphor with a medium-short persistence. Stimulus presentation and data collection were controlled by SuperLab running on a Macintosh II computer.

Procedure. Each trial consisted of three stimulus events. The first signaled the start of a trial with a fixation cross that lasted for 500 msec. The stimulus letter followed for either 16 or 50 msec. A mask terminated the stimulus event and remained on the screen until the subject made a keypress response. The mask was a grating of diagonal lines (0.5 mm wide) with a luminance of 60.77 cd/m^2. It was large enough to cover the stimulus field used in the experiment (15° × 31°). RTs measured the time between the presentation of the stimulus and the subject's keypress response.

Subjects participated individually in sessions of approximately 45 min. A chinrest was used to stabilize head movements and to maintain fixation on the center of the screen. The subjects were instructed to keep their eyes on the fixation cross and to identify the target as quickly as they could by pressing *D* or *K* on the keyboard. Each subject participated in a block of 30 practice trials prior to the experiment, and then in 256 trials that represented 16 replications of 16 experimental conditions. There was a random arrangement of trials that represented four retinal locations factorially combined with two scaling conditions and two exposure durations. The two letters were used equally often across all conditions, and when stimuli appeared in nonfoveal locations, right and left sides of the visual field were used equally often.

Results and Discussion

Means were computed from the correct RTs obtained from each subject across the 16 trials within each of the experimental conditions. RTs in excess of 1,200 msec (less than 2% of the responses) were not included in the analysis. Incorrect responses were also recorded. A $2\times 2\times 4$ repeated measures analysis of variance (ANOVA) was used on the RT and error data to test for the effects of scaling condition, exposure duration, and retinal location. The retinal-location factor collapsed across visual fields and compared differences at 0°, 5°, 10°, and 15° eccentricity. Preliminary data analysis did not show any effects of right or left visual field.

Experiment 1. Scaling condition was found to interact with presentation location [$F(3,81) = 106.92$, $p = .0001$]. In Figure 1a, RTs to the N-scaled stimuli are shown to increase with distance from the fixation point, but a different pattern of data is found with M-scaled stimuli. Foveal responses to M-scaled letters were longer than extrafoveal responses, and no RT differences were observed among the peripheral retinal locations. A simple effect test of retinal location at each scaling condition with additional pairwise comparisons confirmed the significance of the effects within each of the scaling conditions ($ps < .05$). The fact that RTs to the M-scaled stimuli at 5°, 10°, and 15° did not differ from each other confirms the fact that M-scaling was generally effective in equating stimulus visibility.

However, the exceptionally long RT with the foveal scaled stimulus was unexpected and not predicted by cortical magnification theory. There were several factors that could have produced this effect. The most obvious—that the 5-point letter size was too small for the monitor to display clearly—was disputed (1) by the results of Experiment 3, in which the same letter size led to much quicker responses (as Figure 3 shows, mean RT to the small stimulus at the foveal location was around 250 msec, compared with the average response of 400 msec in this experiment); and (2) by the results of Experiment 2, in which M-scaling with a slightly larger foveal letter produced a similar interference effect. A more likely explanation was the mixing of small and large sizes and the relative size difference between the foveal and peripheral stimuli. There is some evidence that visual attention is tuned to scale, and presenting subjects with mixed-scale stimuli may disrupt performance (Cave & Kosslyn, 1989; Farell & Pelli, 1993). Interestingly, mixing the scale seemed to disrupt performance only at the foveal location where the letter size was the smallest. The fact that more errors were made in this condition also suggests that visual attention was disrupted. Experiment 4 investigated this effect in more depth.

The analysis also showed two significant main effects: N-scaled stimuli varied from M-scaled stimuli [$F(1,27) = 30.53, p = .0001$]; and there was an effect of retinal location [$F(3,81) = 42.06, p = .0001$]. However, there was no effect of exposure duration, nor did exposure duration interact with any of the other variables ($Fs < 1$). The effect of exposure duration was consistent at each of the scaling conditions and at each of the retinal locations tested.

Errors. The analysis of the errors also showed an interaction of scaling condition × retinal location [$F(3,81) = 9.08, p = .0001$] and a main effect of scaling condition [$F(1,27) = 6.16, p = .02$]. As indicated in Figure 1b, these effects resulted from the high error rate obtained when the scaled letters appeared in the fovea. Simple effects of retinal location at each scaling condition showed no effect of retinal location among the N-scaled stimuli and a significant effect of location with the M-scaled stimuli that was due to the excessively high error rate obtained in response to the foveally placed stimulus ($ps < .05$). There was no effect of exposure duration, and this variable did not interact with either scaling condition or retinal location ($Fs < 1$).

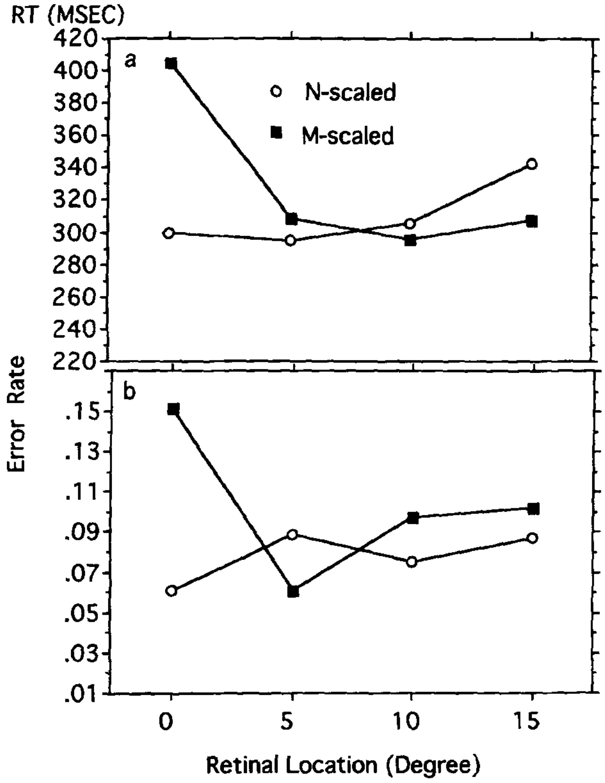

Figure 1. Mean RT and error rate as a function of scaling condition and retinal location in Experiment 1.

Experiment 2. M-scaling with a slightly larger foveal stimulus than in the first experiment resulted in an interaction of scaling condition × retinal location [$F(3,66) = 15.48, p = .0001$], and these two factors together interacted with exposure duration [$F(3,66) = 5.91, p = .001$]. Figures 2a and 2c present the three-way effect. Although there is an elevation in RT at the foveal location, it is much smaller than the effect obtained in Experiment 1 (Figure 1a), and it was limited to the 16-msec duration. When a longer exposure duration was used, RTs for the M-scaled stimuli were consistent across the four retinal locations.

The analysis also showed a main effect of exposure duration [$F(1,22) = 6.75, p = .02$] and an interaction of exposure duration × retinal location [$F(3,66) = 5.91, p = .001$]. At the larger eccentricities only, mean RTs to 16-msec stimuli were quicker than those to the 50-msec stimuli. Differences in RT between the two exposure durations were not evident at foveal or parafoveal locations. As in Experiment 1, there were significant main effects of scaling condition [$F(1,22) = 5.54, p = .03$] and retinal location [$F(3,66) = 22.06, p = .0001$].

Errors. Error rate was found to vary as a function of scaling condition [$F(1,22) = 4.24, p = .05$] and retinal location [$F(3,66) = 3.91, p = .01$]. In general, the error rate increased with distance from the fovea and with the use of M-scaled rather than N-scaled stimuli. Mean error rates for the four retinal locations, in order of distance from the fovea, were 3%, 5%, 7%, and 6%. There was a 5% error rate associated with the N-scaled stimuli and

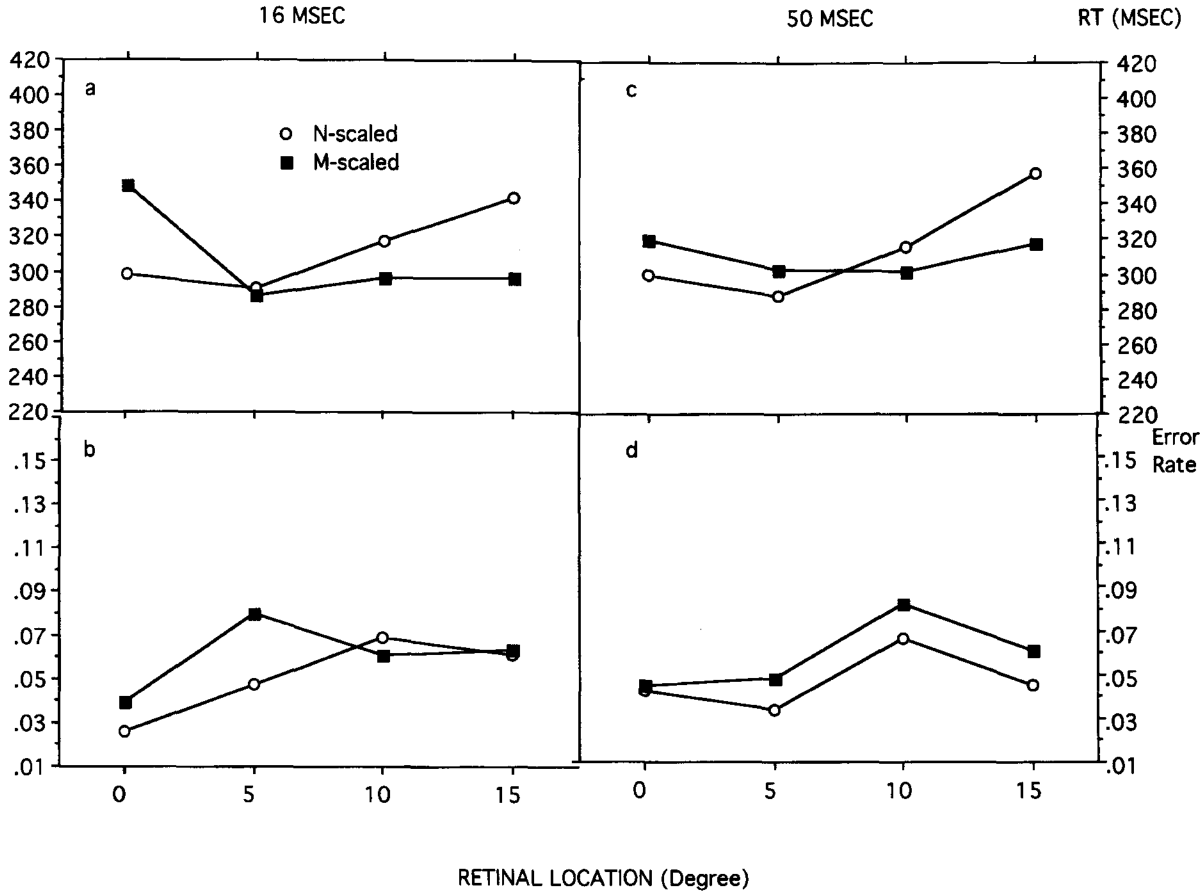

Figure 2. Mean RT and error rate as a function of scaling condition, exposure duration, and retinal location in Experiment 2.

one of 6% for the M-scaled stimuli. The scaling condition × retinal-location effect that was found in Experiment 1 was not significant ($F < 1$). Errors were not affected by exposure duration or by any interaction with this variable (Fs < 1).

The results of Experiment 2 replicate those of Experiment 1 by showing that when letter sizes are scaled in accord with cortical magnification theory, CRTs are found to be equivalent even though stimuli appeared at several retinal locations. CRTs were not found to increase with eccentricity when an M-scaled letter was presented.

The puzzling elevation in foveal RT with M-scaled stimuli was also apparent in these findings. However, the use of a larger foveal letter size (7 points) attenuated the interference effect and limited it to the briefer exposure duration. Since the interference effect was obtained in only one of the two exposure durations and was not large enough to affect the error rate, it does not appear to result from a disruption of attention caused by mixing the scale. A disruption of visual attention would have affected performance across conditions. Most likely the effect is due to a synergy between the exposure duration variable and the foveal letter size. Experiment 4 looked at the relationship between letter size and exposure duration in more depth.

A joint ANOVA on RTs from Experiments 1 and 2 showed that experiment interacted with scaling condition and retinal location in a three-way interaction [$F(3,147) = 11.33, p = .0001$], as well as in two two-way interactions—experiment × scaling condition [$F(1,49) = 31.74, p = .0001$] and experiment × retinal location [$F(3,147) = 15.25, p = .0001$]. Moreover, the results of Experiment 2 differed from those of Experiment 1 in showing some effect of exposure duration, whereby the longer exposure duration was associated with longer RTs. However, this effect interacted with retinal location and, in a three-way interaction, with scaling condition and retinal location. Both exposure durations were long enough to fully process the stimulus letter regardless of presentation location. The longer RTs in the 50-msec condition may have resulted from the subject waiting until the letter disappeared before responding. Such an interpretation would explain why this variable was not found to affect the error rate. The joint ANOVA showed a four-way effect of experiment × exposure duration × scaling condition × retinal location [$F(3,147) = 3.74, p = .01$].

EXPERIMENT 3

Experiment 3 tested scaled sizes derived from Anstis' (1974) regression formula (A-scaling). The two sizes tested at each retinal location included small (near-threshold) and large (suprathreshold) sizes. Since CRTs to constant-sized letters were consistent in the first two experiments, this condition was not included, this experiment focusing instead on a comparison of large and small letter sizes. The larger values were included to test the degree to which the small stimuli may underestimate the sizes needed to scale stimuli at eccentricities larger than 5° of visual angle.

Luminance of the background was also varied in this experiment, together with exposure duration. Some studies (Waugh & Levi, 1993) have shown that visual performance is affected by luminance changes across eccentricity, and lighting conditions (ambient illumination and display luminance) have been shown to affect RTs (Imbeau, Wierwille, Wolf, & Chun, 1989; Krantz, Silverstein, & Yei-Yu, 1992). Bright and dark backgrounds tested whether this variable had any effect on letter detection under peripheral viewing conditions. It was expected that the letters would be more noticeable against a light background, but it was not known whether background luminance would interact with stimulus size or exposure duration. RTs are a measure of the duration of mental processes, and each of the factors tested in this experiment could conceivably add a stage of processing which would lengthen the time taken to respond (Sternberg, 1969).

Method

The subjects were 32 men and women student volunteers. The stimuli and procedure were the same as in Experiments 1 and 2, except in the following respects. Two kinds of backgrounds were used, a bright background with a luminance of 121 cd/m^2 and a dark background with a luminance of 43.68 cd/m^2 (measured with a Minolta luminance meter LS 100).

The stimuli were scaled by increasing their size in accordance with the following regression line for small stimuli: $y = 0.34^\circ + 0.027x$, where y represents the letter's height in degrees of visual angle and x represents retinal eccentricity, also expressed in degrees of visual angle. For large stimuli, the regression line was: $y = 0.74^\circ + 0.027x$. This formula is a modified version of the Anstis (1974) formula, with the intercept value changed to include the two arbitrarily selected foveal values derived from pilot testing with brief stimulus durations and a slightly smaller slope value (.027, compared with .046) to standardize the point changes in letter size with eccentricity. The stimulus letter was presented at one of seven locations on the screen—0°, 5°, 10°, or 15° to the right or left of the fixation point. At 0°, the letter size for the small stimuli was 5 points, and at retinal locations 5°, 10°, and 15°, the letter sizes were increased, respectively, to 7, 9, and 11 points. With the subject seated 30 cm from the screen, the visual angles subtended by the letter heights were, respectively, .34°, .47°, .61°, and .74°. For the large stimuli, at 0°, the letter size was 11 points, and at retinal locations 5°, 10°, and 15° from the fixation point, the letter sizes were increased, respectively, to 13, 15, and 17 points. The visual angles subtended by the letter heights were, respectively, .74°, .88°, 1.02°, and 1.14°.

Each subject participated in 512 experimental trials that represented 16 replications of 32 experimental conditions. The trials were divided into two blocks according to high and low luminance conditions, and blocks were counterbalanced in their presentation to the subjects. Within each block, there was a random arrangement of trials that represented four retinal locations (0°, 5°, 10°, and 15° of visual angle) factorially combined with two stimulus sizes (small and large) and two exposure durations (16 and 50 msec). The two letters were used equally often across all conditions and, in the instances in which stimuli appeared at extrafoveal locations, right and left sides of the visual field were balanced.

Results

Means were computed from the correct RTs obtained from each subject across the 16 trials within each of the experimental conditions. RTs in excess of 1,200 msec (less than 2% of the responses) were not included in the analysis. Incorrect responses made by each subject in each condition were also recorded. A 2×2×2×4 repeated measures ANOVA was used to test for the effects of luminance, size, exposure duration, and retinal location.

The ANOVA on the RTs showed an effect of size $[F(1,31) = 6.16, p = .02]$ and retinal location $[F(3,93) = 22.68, p = .0001]$, and an interaction of size × retinal location $[F(3,93) = 14.65, p = .0001]$. From the data, which are presented in Figure 3a, it appears that RTs to the large stimuli were similar to those to the small stimuli at all locations except 15°. The retinal-location effect was more pronounced with the small stimuli than it was with the large stimuli. However, a test for simple effects of retinal location revealed significant effects with both

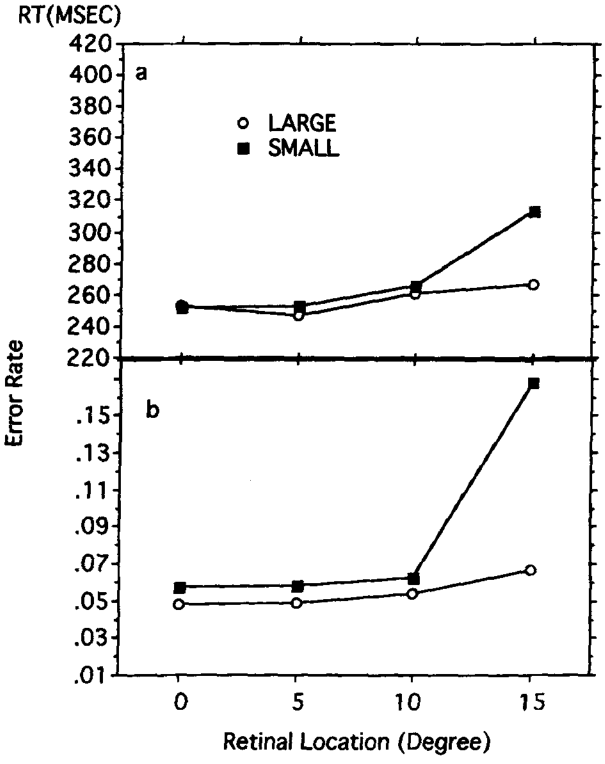

Figure 3. Mean RT and error rate as a function of stimulus size and retinal location in Experiment 3.

large and small stimuli (*ps* < .01). Partial omega-squared values were also calculated to determine the relative importance of the retinal-location effect for both sizes of stimuli (Keppel, 1991). The analysis on the small stimuli showed that 42% of the variance in RTs was accounted for by the retinal-location effect, compared with 6% for the large stimuli.

Retinal location was also found to interact with exposure duration [$F(3,93) = 3.33, p = .02$]. As shown graphically in Figure 4, it appears that the interaction resulted from exposure-duration differences across eccentricity. As in the previous study, RTs were quicker with the shorter duration [$F(1,31) = 74.49, p = .0001$], but the difference varied across eccentricity. Interestingly, there was a slight foveal elevation in RTs associated with the shorter exposure duration. As in Experiment 2, however, the foveal elevation disappeared with a longer exposure duration. There was no main effect of luminance [$F(1,31) = 3.27, p = .08$], and this variable did not interact with any of the others.

Errors. The analysis on the error data show the same retinal-location effect as the RT analysis. There were main effects of size [$F(1,31) = 21.18, p = .0001$] and retinal location [$F(3,93) = 39.19, p = .0001$], and these variables were found to interact [$F(3,93) = 28.83, p = .0001$]. From Figure 3b, which presents the interaction, it is apparent that, as with the RT data, the retinal-location effect is much stronger with the small stimuli than it is with the large stimuli. However, simple effects of retinal location are found with each of the stimulus sizes (*ps* < .05). A comparison of the relative omega-squared values shows a drop in the amount of explained variance resulting from the retinal-location effect, from 53% with the small stimuli to 5% with the large stimuli.

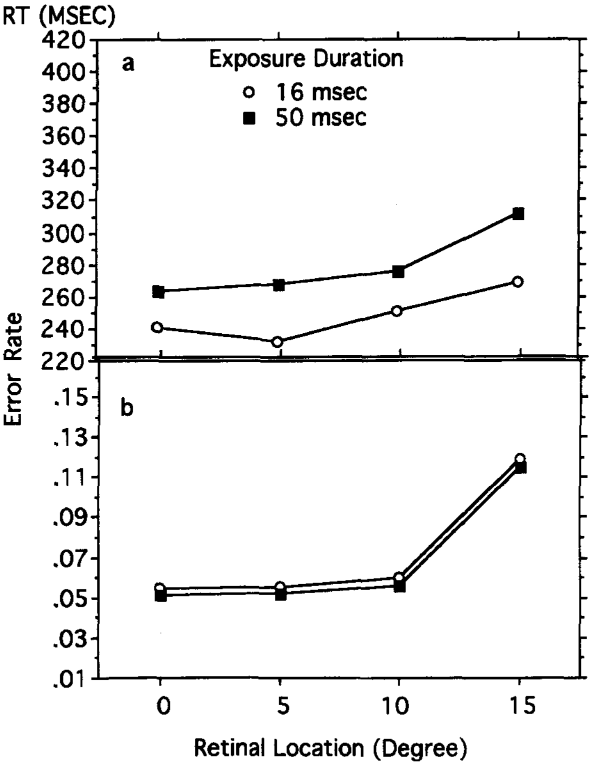

Figure 4. Mean RT and error rate as a function of exposure duration and retinal location in Experiment 3.

None of the other effects in the analysis were significant. Brightness and exposure duration did not significantly influence the error rate.

Discussion

The persistent effect of retinal location in the analysis of both RT and error rate suggests that size scaling with the modified Anstis (1974) formula does not equate visibility when letters are presented at varying presentation locations. A-scaling worked to equate visibility for stimuli that were presented at 5° eccentricity but not for the stimuli presented at further distances from the fovea. Scaling the letters with sizes in excess of the threshold values significantly reduced the magnitude of the retinal-location effect and improved performance for letters presented at 15° eccentricity, but it was not enough to compensate for differences in processing that occur across the visual field. In general, A-scaling provided a good fit for the data at parafoveal eccentricities but underestimated the sizes needed to compensate for resolution differences at large eccentricities. M-scaling, which was similar to A-scaling in that scaled letter sizes were linearly related to eccentricity, provided a better fit to the CRT data because it used a larger slope in scaling letter size with eccentricity.

Although there was a significant interaction of exposure duration and retinal location, the data do not show a substantial effect of this interaction. As in Experiment 2, it appears that 16 msec was sufficient for processing the stimulus letter at each of the locations tested. As indicated in that experiment, the main effect of exposure duration most probably resulted from the subjects waiting to begin responding until the offset of the stimulus.

EXPERIMENT 4

A-scaling and M-scaling were directly compared in Experiment 4 to clarify some of the previous findings. The results of the first two experiments suggested that M-scaling was more effective than A-scaling in equating stimulus visibility, but there was a puzzling elevation in RT associated with the foveal stimulus. The fact that in Experiment 3 the same stimulus size was tested and found to produce much quicker RTs than in Experiment 1 suggested that the foveal elevation in RT was a byproduct of M-scaling with a small foveal stimulus. Perhaps the relative difference between the foveal and peripheral stimulus sizes produced such a size contrast that it impaired visibility, but only with small stimuli.

Experiment 2 showed a reduction in the interference effect when a larger foveal stimulus was used. In Experiment 4, both M- and A-scaling were used with large and small stimuli to determine whether CRTs would be affected by scaling technique and the absolute size of the foveal stimulus.

This experiment also sought to clarify the effect of exposure duration, which, in Experiments 2 and 3, interacted with size and retinal location and seemed to be an influential factor in producing the foveal elevation in RT. To examine the influence of this variable, three exposure durations were tested—25, 50, and 75 msec.

Method

The subjects were 24 men and women student volunteers. In all respects except the following, the stimuli and procedure were the same as in the previous experiments. While sizes for the small M-scaled stimuli at each retinal location were the same as the scaled stimuli used in Experiment 1, the large scaled stimuli were as follows: 11 points at 0°, 30 points at 5°, 48 points at 10°, and 68 points at 15°. With the subjects seated 30 cm from the screen, the visual angles subtended by the letter heights were, respectively, .74°, 2.00°, 3.26°, and 4.59°. The small and large sizes for A-scaling were the same as the stimuli used in Experiment 3. From Table 1, it is apparent that the foveal letter sizes for A-scaling and M-scaling were the same.

Each subject participated in 768 experimental trials that represented 16 replications of 48 experimental conditions. The trials were divided into two blocks according to scaling technique (A- or M-scaling), and blocks were counterbalanced in their presentation to the subjects. Within each block, there was a random arrangement of trials that represented four retinal locations factorially combined with three exposure durations and two stimulus sizes. The two letters were used equally often across all conditions and, in instances in which stimuli appeared at extrafoveal locations, right and left sides of the visual field were balanced.

Results

Means were computed from the correct RTs obtained from each subject across the 16 trials within each of the experimental conditions. RTs in excess of 1,200 msec (less than 2% of the responses) were not included in the analysis. The incorrect responses made by each subject in each condition were also recorded. A 2×2×3×4 repeated measures ANOVA tested for the effects of scaling method, size, exposure duration, and retinal location.

Mean correct RTs for each of the experimental conditions are presented in Figure 5. Although the four-way interaction was not significant ($F < 1$), the analysis did reveal two- and three-way interactions. Retinal location interacted with size [$F(3,69) = 11.47, p = .0001$] and with scaling technique [$F(3,69) = 39.75, p = .0001$], and there was an interaction of retinal location × size × exposure duration [$F(6,138) = 2.35, p = .03$], as well as one of retinal location × size × scaling technique [$F(3,69) = 17.60, p = .0001$]. There were also main effects of all four of the variables of interest—namely, scale [$F(1,23) = 9.45, p = .005$], size [$F(1,23) = 111.64, p = .0001$], exposure duration [$F(2,46) = 4.12, p = .02$], and retinal location [$F(3,69) = 25.99, p = .0001$].

Errors. The error rate was also influenced by several of the manipulated effects. There was an interaction of scale × size × retinal location [$F(3,69) = 8.10, p = .0001$], which resulted from two effects: (1) more errors were made when small A-scaled stimuli were presented at peripheral retinal locations relative to the other ex-

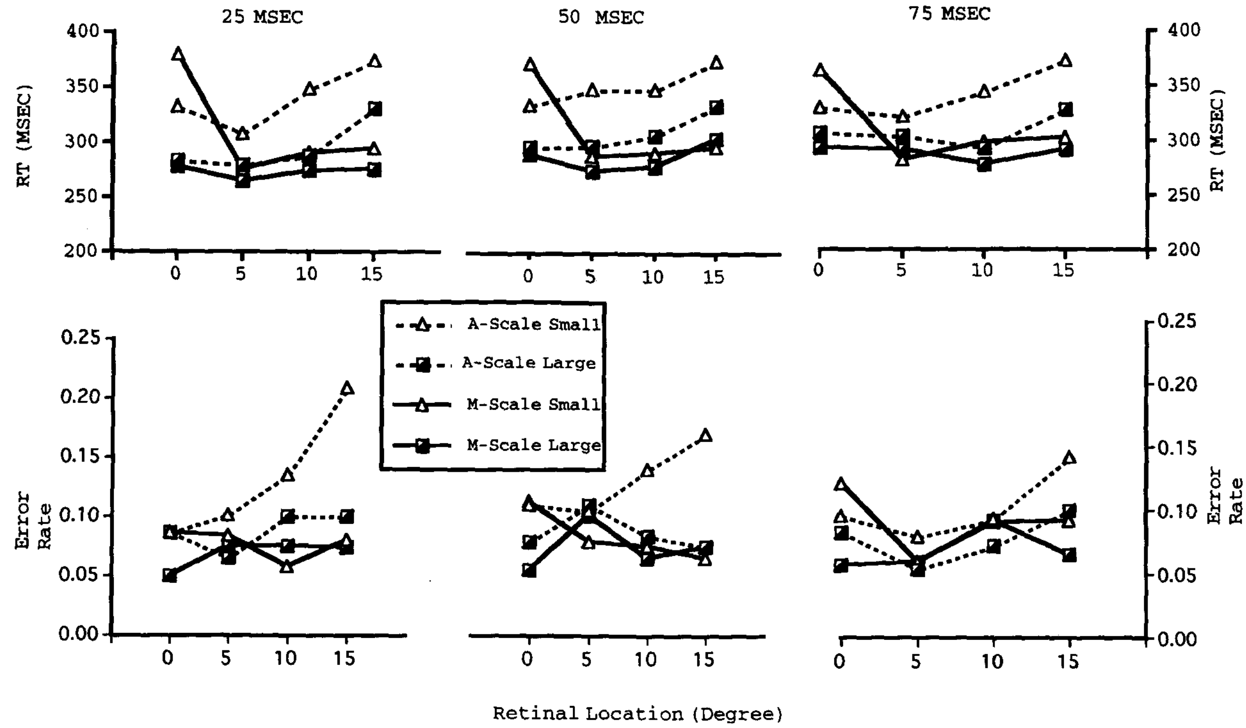

Figure 5. Mean RT and error rate for the experimental conditions in Experiment 4.

perimental conditions; and (2) more errors were made when small M-scaled stimuli appeared at the foveal rather than at the peripheral locations. These effects also produced a retinal location × size interaction [$F(3,69) = 3.83$, $p = .01$], a retinal location × scale interaction [$F(3,69) = 5.74$, $p = .001$], and a size × scale interaction [$F(1,23) = 7.88$, $p = .01$], as well as main effects of scale [$F(1,23) = 4.83$, $p = .04$], size [$F(1,23) = 32.60$, $p = .0001$], and retinal location [$F(3,69) = 4.82$, $p = .004$].

Although there was no main effect of exposure duration on the error rate [$F(2,46) = 1.08$, $p = .35$], this variable was found to interact with retinal location [$F(6,138) = 2.75$, $p = .01$] and with scaling technique [$F(2,46) = 3.40$, $p = .04$]. Errors were more prevalent with A-scaling than with M-scaling, but only at the two shortest exposure durations. There was also a drop in error rate when stimuli appeared for 75 msec at 5° of visual angle.

Discussion

These findings show that the scaling technique derived from cortical magnification theory (M-scaling) is more effective than Anstis (A-) scaling in equating differences in visibility across retinal location. The lingering effects of retinal location obtained in Experiment 3 with A-scaling were replicated in Experiment 4. However, the differences between the scaling techniques are quantitative rather than qualitative. Both techniques involved consistent increases in letter size with eccentricity, but M-scaling used steeper increments that provided a better fit to the CRT data.

Second, Experiment 4 shows that the foveal elevation in RTs is limited to M-scaling with small foveal stimuli. M-scaling with suprathreshold sizes did not show the same effect, even though subjects were exposed to mixed-scale stimuli. It is likely that the foveal elevation in CRTs resulted from a disruption in visual attention. Using the same foveal stimulus within different contexts (i.e., M- and A-scaling) produced different results. The context with the broader range of sizes (M-scaling) produced the interference effect, but only with near-threshold–sized letters. The context with suprathreshold letters did not result in an RT delay. Unlike previous work with M-scaling (Levi et al., 1985), these data suggest that the specific value chosen for the foveal M is important. If it is too small, foveal letter detection is disrupted relative to letter detection at extrafoveal locations.

It is also possible that the foveal interference effect resulted from specific features of the two letters used as stimuli. Since only two letters were tested, it may be that the specific features that made *D* highly discriminable from *K* differ when small and large point sizes are used. The fact that only two letters were used as stimuli does limit the generality of the findings. However, this interpretation is unlikely because it would suggest that RTs would have been delayed with both scaling techniques that used small letters. Since the interference effect was specific to small M-scaled letters, an attentional explanation provides a more convincing rationale for the findings.

Exposure duration had more of an effect on RT performance with A-scaling than it did with M-scaling. The RT difference between small and large A-scaled stimuli was smaller when the letters appeared for 75 msec than it was for the other exposure durations. Responses to M-scaled stimuli, however, did not seem to be influenced by exposure duration.

CONCLUDING REMARKS

The absolute size of the foveal stimulus influenced the effectiveness of the scaling procedures. With both techniques, scaling effectiveness improved when large foveal letter sizes were used. A-scaling with a large foveal letter provided a good fit for the data at parafoveal locations, but underestimated the letter sizes needed at large eccentricities. However, when M-scaling was used with a large foveal letter size, CRTs were found to be independent of eccentricity. These results extend the use of M-scaling to a CRT task with letters as stimuli. To answer the question posed at the outset, M-scaling can be used to equate the visibility of letters when presented at eccentricities from 0° to 15° of visual angle as long as the size of the foveal stimulus is suprathreshold. M-scaling with small foveal stimuli impairs foveal detection. This finding is in contrast to previous work with cortical magnification theory in which the relative difference in stimulus size was emphasized in equating visibility across eccentricity and the absolute size was unimportant.

Exposure duration had more of an effect on RT performance when A-scaling was used than it did when M-scaling was used, but the effect was not substantial and did not indicate any significant difference in the rate of processing information across retinal location. For three of the experiments, RTs were quicker with the briefer exposure durations, suggesting that subjects were waiting until the offset of the stimulus to begin letter responding.

REFERENCES

Alpern, M. (1971). Effector mechanisms in vision. In J. A. Kling & L. A. Riggs (Eds.), *Woodworth and Schlosberg's Experimental psychology* (3rd ed., pp. 369-394). New York: Holt, Rinehart & Winston.

Anstis, S. M. (1974). A chart demonstrating variations in acuity with retinal position. *Vision Research*, **14**, 589-592.

Bijl, P., Koenderink, J. J., & Kappers, A. M. L. (1992). Deviations from strict M scaling. *Journal of the Optical Society of America*, **9**, 1233-1239.

Cave, K. R., & Kosslyn, S. M. (1989). Varieties of size-specific visual selection. *Journal of Experimental Psychology: General*, **118**, 148-164.

Eriksen, C. W., & Schultz, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics*, **25**, 249-263.

Farell, B., & Pelli, D. G. (1993). Can we attend to large and small at the same time? *Vision Research*, **33**, 2757-2772.

Fiorentini, A., & Berardi, N. (1991). Limits in pattern discrimination: Central and peripheral factors. In J. R. Cronly-Dillon (Ed.), *Vision and visual dysfunction* (pp. 266-275). Basingstoke, U.K.: Macmillan.

Imbeau, D., Wierwille, W. W., Wolf, L. D., & Chun, G. A. (1989).

Effects of instrument panel luminance and chromaticity on reading performance and preference in simulated driving. *Human Factors*, **31**, 147-160.

Keppel, G. (1991). *Design and analysis: A researcher's handbook* (3rd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Kitterle, F. L. (1986). Psychophysics of lateral tachistoscopic presentation. *Brain & Cognition*, **5**, 131-162.

Krantz, J. H., Silverstein, L. D., & Yei-Yu, Y. (1992). Visibility of transmissive liquid crystal displays under dynamic lighting conditions. *Human Factors*, **34**, 615-632.

Levi, D. M., Klein, S. A., & Aitsebaomo, A. P. (1985). Vernier acuity, crowding and cortical magnification. *Vision Research*, **25**, 963-977.

Saslow, M. G. (1967). Latency for saccadic eye movement. *Journal of the Optical Society of America*, **57**, 1030-1036.

Smith, E. E. (1968). Choice reaction time: An analysis of the major theoretical positions. *Psychological Bulletin*, **69**, 77-110.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, **30**, 276-315.

Strasburger, H., Harvey, L. O., Jr., & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception & Psychophysics*, **49**, 495-508.

Virsu, V., Näsänen, R., & Osmoviita, K. (1987). Cortical magnification and peripheral vision. *Journal of the Optical Society of America*, **4**, 1568-1578.

Virsu, V., & Rovamo, J. (1979). Visual resolution, contrast sensitivity and the cortical magnification factor. *Experimental Brain Research*, **37**, 475-494.

Waugh, S. J., & Levi, D. M. (1993). Visibility and Vernier acuity for separated targets. *Vision Research*, **33**, 539-552.

Whitaker, D., Makela, P., Rovamo, J., & Latham, K. (1992). The influence of eccentricity on position and movement acuities as revealed by spatial scaling. *Vision Research*, **32**, 1913-1930.

(Manuscript received January 24, 1994;
revision accepted for publication July 12, 1994.)