INTRODUCTION

As one measure from the fovea to the periphery, performance on all known spatial-acuity tasks decreases. The loss of visual acuity from fovea to periphery is also manifest in a variety of physiological measures, including the density of photoreceptors,\(^1\,^2\) the density of retinal ganglion cells,\(^2\,^4\) and cortical receptive-field size.\(^2\,^7\)

Rovamo et al.\(^8\) suggested that, of these various measures, the density of cortical cells is the most important factor in limiting the detectability of targets presented at different locations in the visual field (see also Ref. 9). To test this hypothesis, Rovamo et al.\(^8\) used data from the electrical phosphene studies done by Brindley and Lewin\(^10\) with awake human patients to estimate the amount of cortical area per degree of visual angle at different retinal eccentricities. Rovamo et al. scaled the sizes of their visual stimuli at different retinal eccentricities so that stimuli at different retinal eccentricities would project onto the same area of visual cortex. Their measurements support the hypothesis that, if visual stimuli are scaled for equal cortical area, then the stimuli will be equally detectable. The required scaling, measured as a function of eccentricity, is called the inverse cortical magnification factor.

The fact that the estimate of the required scaling obtained by Rovamo et al.\(^8\) is approximated by a linear scaling function greatly simplifies the characterization of the scaling required for equal detection performance from fovea to periphery. Others, including Kelly\(^11\) and Levi et al.,\(^12\) confirmed and extended the basic measurements of Rovamo et al. by using other types of detection and simple discrimination tasks.

In this paper we consider the hypothesis that there is a single scaling function required for identification of a target. The simplest hypothesis concerning target identification is that the only limit imposed is that of the visibility of the target. In that case, the threshold detection and discrimination values provide an estimate of the quality of information. Once we have corrected for the detection threshold, by an appropriate size scaling, we might expect that targets would be equally identifiable. An alternative hypothesis is that the visual system is designed with the assumption that the quality of spatial information in the visual periphery is generally too poor to play a role in the identification of objects. For example, Handel and Christ\(^13\) suggested that the detection and identification of visual targets are independent visual processes, on the grounds that the detectability of simple geometric targets at different retinal locations is not correlated with the identifiability of the targets at the same retinal locations. Rather than devoting resources to the identification of targets in the periphery, the visual system might instead execute an eye movement to foveate the stimulus. In this case, identification processing would be worse in the periphery than in the central viewing regions, and no scaling function would render targets presented in the periphery as identifiable as targets presented in the fovea.

By a linear scaling of stimulus size with stimulus eccentricity the detectability of a stimulus can be maintained at a constant performance level.\(^5,11\) In this paper, we test two hypotheses that extend this observation. First, we test the hypothesis that when the stimulus size is scaled linearly with stimulus eccentricity the identifiability of a stimulus set remains at a constant level. Second, we test the hypothesis that the identifiability of a pair of stimuli, presented simultaneously at different eccentricities, can be predicted by assuming independent contributions from the two stimuli.

EXPERIMENT 1

The purpose of experiment 1 was to determine whether there exists a scaling of stimulus size with stimulus eccentricity that will maintain the identifiability of individual alphanumeric characters across the visual field. In order to measure a person's ability to identify information, digits of different sizes were presented briefly at different retinal eccentricities, and subjects were asked to identify each digit. After each trial, subjects were given feedback. The amount of information transmitted at each eccentricity over a range
of sizes was computed from stimulus–response confusion matrices. The information transmitted was used to test the hypothesis that there exists a size scaling of stimulus size with retinal eccentricity that equates the amount of information transmitted across retinal location.

**Method**

**Subjects**

Data were collected from four observers, including the authors (JF and MD). All observers had normal or corrected-to-normal vision.

**Stimuli**

On each trial the subject was briefly presented with 10 possible digits, 0 through 9, on a 19-in. (approximately 48-cm) Hitachi color cathode-ray tube (CRT) controlled by a Silicon Graphics IRIS 2400 computer. The stimuli appeared as blue digits presented against a constant white background. The stimulus presentation time was less than 10 msec.

Stimulus luminance was estimated by addressing every pixel at the intensity value used to draw the digits and averaging the luminance within the 2.4-mm aperture of a Minolta spotmeter. Using this procedure, we estimated that the stimuli were drawn with line elements that had an average luminance of 3.17 cd/m². Similarly, background luminance was measured by addressing every pixel at the intensity value used to draw the white background and averaging the luminance within the 2.4-mm aperture of the Minolta spotmeter. The average background luminance was approximately 19.5 cd/m².

Stimuli were presented in blocks of 160 trials. In each block, the digits were presented in one retinal size and at one retinal eccentricity. Within each block of trials, the digits could occur in one of eight equally likely positions centered about the fixation point obtained by displacing each digit R deg of visual angle from the center of fixation (where R = 1.879, 3.754, or 8.122) in a direction oriented A deg from the vertical, where A = 0, 45, 90, . . . , 315.

Digits presented at 1.879 deg of retinal eccentricity subtended 15, 18.6, 22.2, 22.8, 28.2, and 33.6 min of visual angle. Digits presented at 3.754 deg of retinal eccentricity subtended 22.2, 22.9, 33.6, 36.6, 44.4, and 55.2 min of visual angle. And digits presented at 8.122 deg of retinal eccentricity subtended 36.6, 51.0, 55.2, 66.0, 76.3, and 98.4 min of visual angle.

Each experimental session consisted of 160 digits presented at a particular size and eccentricity. The identity and screen position of each digit were ordered randomly within each block of 160 trials. Each experimental session was preceded by 20 practice trials, randomly selected from the 160 trials that followed. Over the course of a week, subjects viewed 18 blocks of trials that differed in the size and retinal eccentricity of the stimuli (six different stimulus sizes and three different retinal eccentricities), yielding a total of 2,880 trials.

**Procedure**

Each subject sat in front of the CRT display on which the stimuli were presented. The subject's head was positioned inside a head brace that was situated 2 ft (approximately 0.6 m) away from the CRT display. The subject initiated a stimulus trial by pushing the space bar of a keyboard. After the space bar was pressed, a cross-hair fixation point was displayed on the CRT at the center of the screen for 1 sec. This was followed immediately by a brief presentation of a digit of a given size and retinal eccentricity in one of eight equally likely positions. The subject was instructed to keep his or her gaze centered on the cross hair and to identify the digit that was presented. After deciding which digit was presented, the subject was given feedback about the correct answer.

**Results and Discussion**

For each of the 18 conditions (three different retinal eccentricities and six different stimulus sizes) a stimulus–response confusion matrix was obtained. Shannon's information-transmitted measure was used as a measure of the identifiability of the target set. Each matrix was used to derive the amount of information that was transmitted in that condition. The amount of transmitted information, I, is based on the values that fall on the diagonal of the stimulus–response confusion matrix. When subjects make no errors, the probabilities in the stimulus–response confusion matrix are all one along the diagonal and zero elsewhere. This is the condition under which the amount of transmitted information is maximum. As the probability values become uniformly distributed across the entries of the matrix, the amount of transmitted information decreases to zero.

To compute the information transmitted we first compute the stimulus and response entropies. The stimulus entropy is \( H(x) = \sum_{i=0}^{6} p_i \log_2(p_i) \), where \( p_i \) is the probability of presenting the \( i \)th target stimulus. The response entropy is \( H(y) = -\sum_{j=0}^{6} q_j \log_2(q_j) \), where \( q_j \) is the probability of response \( j \). Finally, we compute the joint entropy \( H(x, y) = -\sum_{i=0}^{6} \sum_{j=0}^{6} p_{ij} \log_2(p_{ij}) \), where \( p_{ij} \) is the probability of stimulus \( i \) and response \( j \). The information is \( I(x) + H(y) - H(x, y) \). The maximum information in this experiment is 3.32 bits.

In Fig. 1 we plot the information transmitted as a function of the log of stimulus size for each of the four subjects. The different curves are parameterized by viewing eccentricity. Each curve represents data cumulated over 960 observations. Figure 1 shows that at each retinal eccentricity the amount of information transmitted increases with the size of the digits in the target set. In each panel, the curve on the left is for the targets closest to the fovea, 1.879 deg (visual angle) from the central fixation point. The curve on the right is for targets presented 8.122 deg from the fovea. For the same rate of information transmission to be achieved, the size of targets in the visual periphery must be increased.

We tested the hypothesis that there is a scaling function that will yield equal information-transmission characteristics across the observer's visual field. This hypothesis, referred to as the scaling hypothesis, predicts that the amount of information transmitted should be a function of the stimulus size and that the only difference in the functions for targets presented at different locations in the observer's visual field should be a scale factor that depends on the retinal eccentricity of the target. Notice that it makes sense to define a single scaling function only if the function can be defined independently of the performance level. This requires that the curves plotted here, against the logarithm of stimulus size, be parallel. If the curves are not parallel, then...
Fig. 1. Transmitted information (expressed in bits) plotted as a function of the log of stimulus size for each of four subjects. Stimulus size is expressed in minutes of arc and ranged from 15 to 98.4 arcmin. The data for each subject are parameterized by stimulus retinal eccentricity: Circles, triangles, and squares represent data for retinal eccentricities of 1.879, 3.754, and 8.122 deg of visual angle, respectively. Curves passing through the data points represent best-fitting psychometric functions (see the text).

the scaling function would be different for each performance level. The smooth curves shown through the data are all parallel on this logarithmic axis.

To estimate the scaling function required for equal information transmission, we fitted the observed data to a common function of size, differing only by a scale factor that depends on eccentricity. For convenience, a modified Weibull psychometric function was used. The analytic form of the Weibull function is

$$I(s, x) = I_{\text{max}} \left(1.0 - \exp\left[\frac{s}{\alpha(x)}\right]\right),$$

where $s$ is the stimulus size, $x$ is the stimulus retinal eccentricity, and $I_{\text{max}}$ is the maximum amount of information possible, which, in this experiment, was 3.32 bits. When this formulation is used, the ratio $\alpha(x)/\alpha(\text{fovea})$ is the magnification factor.

Whereas, in general, the Weibull function has two free parameters, $\alpha$ and $\beta$, analysis of our data reveals that $\beta = 2.0$ is a good approximation for all subjects at all eccentricities. Across all four subjects, the root-mean-square error (rmse) for the fit between the Weibull function and the data ranged between 0.09 and 0.37. When $\beta$ is free to vary, the Weibull function is improved only slightly. (The rmse ranged between 0.05 and 0.37 when $\beta$ was free to vary.) The Weibull functions in Fig. 1 provide a reasonable approximation to the data points.

The estimated relationship between the scaling factor, $\alpha(x)$, and retinal eccentricity is shown in Fig. 2. The scaling values in this figure can be described by a linear function of the form $\alpha(x) = \alpha + bx$, where $x$ is the retinal eccentricity of a visual target. Since $\alpha(x)$ was not constrained to depend on eccentricity in any way, this function describes an empirical

For each eccentricity, $x$, the scale parameter, $\alpha(x)$, was estimated by using an iterative procedure\textsuperscript{17} that minimized the difference between the observed amount of transmitted information and the amount of information predicted by Eq. (1) (where $\beta = 2.0$ and $I_{\text{max}} = 3.32$). The smooth curves in Fig. 1 provide a reasonable approximation to the data points.

Fig. 2. Scaling factor, $\alpha$, plotted as a function of retinal eccentricity, $x$, for each of four subjects.
relationship between the scale parameter, \( \alpha \), and the retinal eccentricity of the target, \( x \), and supports the hypothesis that there exists a scaling of stimulus size with stimulus eccentricity that will maintain the identifiability of individual alphanumeric characters across the visual field. If the sizes of visual characters are scaled as a function of retinal eccentricity, \( x \), by the appropriate scaling factor, \( \alpha(x) \), then the characters will be equally identifiable. This result implies that it is possible to enhance our ability to identify, as well as to detect, objects by linearly scaling stimulus size with stimulus eccentricity.

From our measurements we can calculate how much a target presented at location \( x \) is scaled compared with a target presented at the fovea. This is simply

\[
\hat{\alpha}(x) = \frac{\alpha(x)}{\alpha(0)} = \frac{a + bx}{a} = 1 + \frac{b}{a} x.
\]  

The parameter \( b/a \) provides an estimate of the scaling function. The data from our four subjects yield an estimate of \( b/a = 1.844 \) and has units of inverse degrees of visual angle. When \( x = a/b \), the stimulus must be doubled to obtain equal performance. (Some authors prefer to use the \( x \) intercept, which is obtained from \( 0 = a + bx \) so that \( x_0 = -a/b \).)

In Fig. 3 the normalized scaling function, \( \hat{\alpha}(x) \), derived from the results of Virsu and Rovamo\(^5\) on grating detection, is compared with \( \hat{\alpha}(x) \) derived from our measurements. This comparison suggests that identification of a visual target requires much more magnification than does detection. Figure 3 also shows a comparison of the normalized scaling functions for character identification and grating detection with a normalized scaling function derived from data published by Ludvigh\(^8\) on visual acuity. Ludvigh measured subjects’ ability to identify letters on a Snellen chart and derived acuity estimates based on the letter size associated with 60% correct letter-identification performance. The scaling function derived from Ludvigh’s data is consistent with the hypothesis that identification of a letter requires slightly more magnification than does grating detection. However, the magnification factor required for 60% correct letter identification is less than the magnification required for equivalent letter-identification performance reported here.

Differences in the scaling functions for identification of single digits and the detection of visual gratings may also reflect differences in the task, the stimuli, or the subject population or some combination of these factors. We discuss possible explanations for the variability in the scaling functions for detection, discrimination, and identification in the General Discussion section of this paper.

**EXPERIMENT 2**

To apply the results of experiment 1 to more-complex displays, displays in which multiple characters or targets are often presented, we must measure the rules of combination for the presentation of several target letters at once. We have performed a mixture experiment to estimate the information transmitted at different eccentricities and scalings for pairs of targets. The experimental stimuli were the same as in the first experiment, but instead of being presented with a single digit, subjects were presented with a pair of digits differing in size and retinal eccentricity. If the information is transmitted independently at the two separate visual locations, then the stimulus–response confusion matrices for each of the digits will be the same as the stimulus–response confusion matrices in the first experiment in which the subject was asked to identify only a single digit.

**Method**

**Subjects**

Two of the four subjects in the previous experiment (jf and md) served as subjects in this experiment.

**Stimuli**

Under one experimental condition, referred to as the single-digit condition, each stimulus consisted of a single digit, one of 10 equally likely digits, 0 through 9, as in experiment 1, and could occur in one of eight possible positions centered about the fixation point. Subjects were presented with nine different blocks of trials under the single-digit condition. Each block of trials consisted of 80 trials (10 digits and 8 positions), preceded by 20 practice trials. Across the nine different blocks of trials, digits differed in size and retinal eccentricity. Digits presented at a retinal eccentricity of 1.879 deg of visual angle subtended visual angles of 12.65, 15.12, and 17.58 arcmin. Digits presented at 3.754 deg subtended 20.03, 24.96, and 29.88 arcmin. Digits presented at 8.122 deg subtended 37.23, 47.89 and 58.55 arcmin. This condition is a replication of the first experiment.

In another condition, referred to as the pairwise-digit condition, subjects were presented with a pair of digits differing in size and retinal eccentricity. The stimuli for the pairwise-digit condition were created by simultaneously presenting two targets from the single-digit condition with the constraint that the two stimuli differ in retinal eccentricity. Over the course of 1 week, subjects viewed a total of 18 blocks of trials: 9 blocks of trials in the single-digit condition and 9 blocks in the pairwise-digit condition. Within each block of trials, the order of stimulus trials was randomized. The order in which the 18 blocks of trials were pre-
sent to the subject during the entire course of the experiment was also randomized with the constraint that single- and pairwise-digit conditions alternate.

Procedure
As in experiment 1, subjects were instructed to keep their gaze centered on a cross-hair fixation point and to identify the digits that were presented. After deciding which digits were presented, subjects were given feedback about the correct answer.

Results and Discussion
Figure 4 shows the information transmitted as a function of retinal eccentricity and digit size for the single- and pairwise-digit conditions. The curves passing through the data points correspond to the best-fitting psychometric functions [see Eq. (1)] derived from the data for the single-digit condition. The points plot the information transmitted as estimated for the pairwise-digit condition. For each subject and each condition of retinal eccentricity, the data for the pairwise-digit conditions fall close to the psychometric functions derived from the data for the single-digit condition. The data show that there is little difference between the amount of information when the targets were presented alone and the amount transmitted when they were presented in pairs.

To explore this result further, the best-fitting parameters of Eq. (1) were derived from the data in the pairwise-digit condition by analyzing identification performance for each member of the two-digit pairs as a function of retinal size and eccentricity. As in experiment 1 the β parameter of Eq. (1) was constrained to be 2.0, and best estimates for α(x) were obtained for digits presented at each of the three retinal eccentricities x. The α(x) that caused the rmse of the fit to double defined the upper bound of the confidence interval around the estimate of α(x).

For subjectjf, the estimates of α(x) derived from the data for the pairwise-digit condition all fall within the confidence interval of the estimates of α(x) derived from the data for the single-digit condition. This result supports the conclusion that the amount of information that a digit transmits is the same when it is presented alone as when it is presented as a member of a digit pair. Moreover, the estimates of α(x) for both the single- and the pairwise-digit conditions fall within the confidence interval for the estimates of α(x) derived from the data obtained in experiment 1. This latter result indicates that the results of experiment 1 were replicated in experiment 2.

For subjectmd, two of the three estimates of α(x) derived from the data obtained for the pairwise-digit condition fall within the confidence interval for α(x) for the single-digit condition. However, all six estimates of α(x) derived from the data obtained for the single- and pairwise-digit conditions fall within the confidence intervals for α(x) estimated in experiment 1. Again, this result indicates that the results of experiment 1 were replicated in experiment 2. [The correlations among the three estimates of α(x) derived from the single-digit conditions of experiments 1 and 2 are 0.995 and

![Fig. 4. Transmitted information (expressed in bits) plotted as a function of the log of stimulus size for each subject for the single- and pairwise-digit stimulus conditions (see the Stimuli subsection for experiment 2 for an explanation of the single- and pairwise-digit conditions). The data for each subject are parameterized by stimulus retinal eccentricity: Circles, triangles, and squares represent retinal eccentricities of 1.879, 3.754, and 8.122 deg of visual angle, respectively. Curves passing through the data points represent best-fitting psychometric functions derived from the data for the single-digit condition.]}
0.998 for subjects jf and md, respectively.] Our comparisons of the best-fitting psychometric functions for experiments 1 and 2 for each condition of retinal eccentricity, x, indicates that the scale factor, \( \alpha(x) \), is nearly the same for digits presented alone as for digits presented in pairs. This result supports the hypothesis that, for a small number of targets that are widely separated spatially, the amount of information transmitted from the screen to the observer can be approximated as the sum of the information transmitted at different locations.

**GENERAL DISCUSSION**

The results of experiments 1 and 2 are consistent with the hypothesis that the mechanisms underlying visual detection, discrimination, and identification are qualitatively the same in the fovea and the periphery except for a scaling of resolution with retinal eccentricity.\(^9\)\(^{10}\)\(^{20}\) Just as there is a scaling function that renders visual targets at different retinal eccentricities equally detectable and discriminable, there is a scaling function that renders the targets equally identifiable.

Quantitatively, the scaling functions derived from performance in visual detection, discrimination, and identification tasks across retinal eccentricity differ in the exact values derived for \( b/a \). Although it appears that the size scaling factor required to equate character-identification performance across retinal eccentricity is greater than the scaling factor required to equate grating-detection performance,\(^12\) quantitative differences between the scaling functions for character identification and grating detection (see Fig. 3) might be due to measurement error and/or individual subject differences. For example, in experiment 1 individual estimates of \( b/a \) ranged between 0.68 and 11.11. Estimates of \( b/a \) derived from data reported by Westheimer\(^21\) on grating resolution for two subjects are 0.27 and 1.67. These individual subject differences span the range of variability in estimates of \( b/a \) derived from the data reported for visual detection and discrimination tasks (see e.g., Levi et al.\(^13\)).

Anstis\(^22\) reported that the size required to obtain 100% correct performance on a letter-identification task increases with retinal eccentricity, supporting the hypothesis that there is a single scaling function that renders visual targets equally identifiable. However, the intercept of the best-fitting linear scaling function derived from Anstis’s data is negative, raising doubts about the descriptive value of the scaling function. Anstis pointed out that the negative intercept of the scaling function must be due to measurement error, since a character must have a positive size in the fovea to be detected.

A second source of variability may result from processing demands imposed by different stimuli and/or different tasks.\(^20\) For example, variability in the parameters of scaling functions depends on the orientation of the spatial-frequency components in a stimulus and on the retinal eccentricity of the stimulus. In the fovea, grating detection is better for horizontal and vertical orientations than for oblique ones.\(^23\) These and other spatial anisotropies in the visual field will contribute to variability in scaling functions for detection, discrimination, and identification of complex patterns such as alphanumeric characters that have spatial-frequency components in many directions. The oblique effect (described above) disappears when stimuli are presented at retinal eccentricities greater than 20 deg (Ref. 24) and is replaced by a so-called meridian effect. The meridian effect refers to the observation that when gratings are presented at retinal eccentricities greater than 20 deg of visual angle, detection performance is best when the grating orientation is parallel to an axis passing through the center of the visual field along a meridian in the visual field.\(^25\) The meridian effect implies that the parameters of scaling functions for grating detection differ depending on grating orientation. The fact that the meridian effect replaces the oblique effect when the retinal eccentricity of grating stimuli is greater than 20 deg of visual angle may explain why estimates of \( b/a \) derived from the results of Rovamo et al.\(^9\) and Virsu and Rovamo\(^9\) are 1.6 when based on retinal eccentricities between 0 and 30 deg and 0.44 when based on retinal eccentricities less than 14 deg.

Finally, data reported by Thomas\(^26\) support the hypothesis that the scaling factor required to equate grating detection is the same scaling factor required to equate grating identification. Thomas compared the ability to detect a low-contrast grating at different retinal eccentricities with the ability to identify the spatial frequency or orientation of the grating and found that, at all retinal eccentricities, identification performance is always proportional to detection performance. Moreover, for grating stimuli with spatial frequencies less than 8 cycles/deg, the ratio between identification and detection performance is constant across retinal eccentricities. This result indicates that performance on grating detection and grating identification decreases at the same rate with retinal eccentricity. For grating stimuli with spatial frequencies centered on 8.0 to 8.5 cycles per degree, Thomas found that the ratio was constant for retinal eccentricities of 5 to 10 deg of visual angle and decreased with retinal eccentricities greater than 10 deg. This result is consistent with the hypothesis that the sensitivities of spatially-tuned visual mechanisms shift to lower frequencies in the visual periphery, as predicted by the cortical magnification factor.\(^8\)^\(^9\)^\(^11\) such that the 8.5-cycle/deg gratings are beyond the upper limit for spatial-frequency discrimination in the visual periphery. The presence of 8.5-cycle/deg gratings at retinal eccentricities greater than 10 deg of visual angle presumably were detected by mechanisms tuned to lower spatial frequencies.\(^27\)

In light of the documented variability in the parameters of the scaling function, we cannot make any definitive statements regarding quantitative comparisons of the scaling functions for detection, discrimination, and identification. If we ignore possible quantitative differences in the scaling functions, the fact that scaling functions have the same general form suggests that the mechanisms underlying visual detection, discrimination, and identification are qualitatively the same.

The second finding of this study, reported in experiment 2, is that the information transmitted by two characters presented simultaneously at different retinal eccentricities can be predicted by the sum of the information transmitted at the two locations.

Additivity defines an upper limit on performance for small target sets. One might expect additivity to become an inaccurate predictor, however, as the stimuli become closer and begin to mask each other\(^29\) or as the number of stimuli
increases and begins to exceed the limitations of short-term visual memory. In particular, one might expect additivity to fail when the total number of characters that the subject must identify in a single glance is greater than four. This failure of additivity would reflect an upper bound on the number of independent visual symbols that can be encoded and stored in short-term visual memory.\(^{29}\)

If we assume that, for target sets of less than four characters, the information transmitted per target is additive, then we can calculate the information transmitted per eye fixation. Assume that, owing to visual-memory limitations, observers can process only four characters per eye fixation. This assumption is supported by eye-fixation patterns recorded by Morrison and Rayner.\(^{30}\) The total amount of information transmitted per eye fixation can be calculated by using the scaling functions for character identification [see Eqs. (1) and (2)] under the assumption of additivity. To simplify the calculation, we consider displays limited to four-digit numbers. The digit in each of the four positions of the character string is equally likely to be one of 10 possible values, 0 through 9.\(^{31}\) We further assume that the observer is fixated at the center of a four-digit character string and that the characters are spaced such that the distance between adjacent characters is 1.053 times the nominal character height, as is illustrated in Fig. 5.\(^{32}\)

Under these constraints, the information transmitted per character depends on the retinal eccentricity and the size of the digit. To predict the total amount of information transmitted by four digits, we simply add up the information transmitted per digit, given the size and retinal eccentricity of each digit. Figure 6 shows the total amount of information that a four-digit string is predicted to transmit as a function of character size (if we assume that additivity applies). Note that the function increases with character size and approaches an asymptote at approximately 0.25 deg of visual angle. This suggests that, when character size is greater than 0.25 deg of visual angle, four-digit strings transmit the same amount of information. It is interesting to note that the rapid decrease in visual acuity with retinal eccentricity is compensated for completely by the increase in character size for retinal sizes greater than 0.25 deg. This result is consistent with the results of Steedman and Baker,\(^{33}\) who found that search time decreases with target sizes less than or equal to 0.25 deg of visual angle and approaches an asymptote thereafter. The result is also consistent with the findings of Legge et al.,\(^{34}\) who found that error-free reading rate increased with character size less than or equal to 0.3 deg of visual angle. For character sizes greater than 0.3 deg of visual angle, the error-free reading speed was constant until character sizes were 2 deg or greater, at which point error-free reading speed declined. Legge et al. also observed eye-fixation patterns consistent with the theory that people are limited to four or five character per eye fixation. The fact that reading speed approaches an asymptote at approximately 0.3 deg of visual angle suggests that, for character sizes greater than 0.3 deg, the decrease in visual resolution with retinal eccentricity can be compensated for by increasing the size of characters. The fact that reading speed declines at greater than 2 deg of visual angle reflects the fact that the retina has a limited extent: thus at some point, the larger the character, the fewer characters will be read by a retina with finite spatial extent.

The calculations outlined above illustrate the predictive power of scaling functions when combined with the assumption that, for small character strings, the total information transmitted by any particular string can be predicted by the sum of the independent contributions of each component character. The results of experiment 2 support the additivity assumption for strings composed of two characters. In the future, we hope to extend the experimental paradigm used in experiment 2 to investigate the information transmitted by longer character strings to determine the point at which additivity no longer applies and thereby to test the predicted memory limitations of short-term visual memory.

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REFERENCES AND NOTES

16. G. A. Miller, "What is information measurement?" Am. Psychol. 8, 3-11 (1953).
31. Although it is possible to generalize the calculation to all alphanumeric characters, one must include information about the probability of letter strings that are, in turn, dependent on the frequency of words that an observer is likely to encounter.
32. Unfortunately, there are no documented rules or procedures for selecting the character spacing that is appropriate for a given character size. Type designers typically adjust the character spacing and in some cases the character forms themselves until the character spacing looks visually pleasing. [See, for example, C. Swann, Techniques by Typography (Lund Humphries, London, 1969), pp. 33-37; R. Labuz, Typography and Typsetting (Van Nostrand Reinhold, New York, 1988), pp. 69-71].
33. The character spacing selected for this calculation was suggested to us by Stuart Center, a digital typographer at Hewlett-Packard, Palo Alto, California.