Acuity is the most commonly used measure of visual function, and reductions in acuity are associated with most eye diseases. Metamorphopsia—a perceived distortion of visual space—is another common symptom of visual impairment and is currently assessed qualitatively using Amsler (1953) charts. In order to quantify the impact of metamorphopsia on acuity, we measured the effect of physical spatial distortion on letter recognition. Following earlier work showing that letter recognition is tuned to specific spatial frequency (SF) channels, we hypothesized that the effect of distortion might depend on the spatial scale of visual distortion just as it depends on the spatial scale of masking noise. Six normally sighted observers completed a 26 alternate forced choice (AFC) Sloan letter identification task at five different viewing distances, and the letters underwent different levels of spatial distortion. Distortion was controlled using spatially band-pass filtered noise that spatially remapped pixel locations. Noise was varied over five spatial frequencies and five magnitudes. Performance was modeled with logistic regression and worsened linearly with increasing distortion magnitude and decreasing letter size. We found that retinal SF affects distortion at midrange frequencies and can be explained with the tuning of a basic contrast sensitivity function, while object-centered distortion SF follows a similar pattern of letter object recognition sensitivity and is tuned to approximately three cycles per letter (CPL). The interaction between letter size and distortion makes acuity an unreliable outcome for metamorphopsia assessment.

Introduction

Acuity quantifies the spatial resolving capacity of the visual system, or the ability to distinguish between two high contrast stimuli separated in space (Kniestedt & Stamper, 2003). It is a commonly used measure of visual function, with loss of acuity associated with many eye diseases, and it is almost always used as an outcome measure for ophthalmology clinical trials and treatment interventions (Age-Related Eye Disease Study 2 Research Group et al., 2014; Beck et al., 2007; Brown et al., 2006). Letter charts such as the Snellen Acuity and ETDRS (Bailey & Lovie-Kitchin, 1976) are used to quantify longitudinal remediation or regression in patients suffering from vision loss, yet there are some discrepancies regarding the accuracy and reliability of visual acuity and its ability to assess overall visual function. The test–retest reliability of the measurement is notably low (Rosser, Cousens, Murdoch, Fitzke, &
Laidlaw, 2003), being three letters for normally sighted people (Arditi & Cagenello, 1993; Patel, Chen, Rubin, & Tufail, 2008).

Many patients with macular disease have reduced visual acuity, which is thought to contribute to their problems with everyday visually guided behaviors such as reading and face discrimination (Rubin, Muñoz, Bandeen-Roche, & West, 2000). There is evidence that visual acuity can be improved by treatment, particularly in patients with wet age-related macular degeneration who are receiving anti-vascular endothelial growth factor injections (Avery et al., 2006; Chang et al., 2007; Fung et al., 2007), and surgery for epiretinal membrane (Suh, Seo, Park, & Yu, 2009) and macular hole (Christensen et al., 2010; Itoh, Inoue, Rii, Hiraoka, & Hirakata, 2012). Although improved acuity correlates with increased quality of life measures (Slakter & Stur, 2005), other symptoms including perceived spatial distortion (metamorphopsia) and reduced contrast sensitivity can persist after treatment (Liem, Keunen, van Meel, & van Norren, 1994; Richter-Mueksch et al., 2007; Tolentino, Miller, Gaudio, & Sandberg, 1994; Wittich, Overbury, Kapausta, & Faubert, 2005).

Letter identification, commonly used in acuity measures, is likely vulnerable to spatial distortion because it requires not only the detection and discrimination of high contrast stimuli, but also involves processing of form and shape. Unlike acuity, metamorphopsia is rarely used as an outcome measure and is commonly assessed qualitatively with Amsler grid charts (Amsler, 1953; Marmor, 2000). Structural changes in the retina are observed in many eye diseases (Itoh et al., 2012; Jaffe & Caprioli, 2004; Wang et al., 2005; Wolf-Schnurrbusch, Enzmann, Brinkmann, & Wolf, 2008; Yi et al., 2009), and we hypothesize that these changes may lead to relocation of photoreceptors and ganglion cells that may contribute to both reductions of visual acuity and the presence of metamorphopsia. Additionally, retinal prostheses remap the coordinates between real world and retinal positions and introduce spatial distortions (for review see Margalit et al., 2002). In simulations of prosthetic vision, such distortions can impair object recognition (Guo et al., 2010) and may benefit from inverse-distortion correction (Chundi, Subramaniam, Muthuraj, & Margalit, 2013; Subramaniam, Chundi, Muthuraj, Margalit, & Sim, 2012). Previous work has shown that spatial distortions are difficult to perceive in natural images, and the detectability of visual distortion is dependent on its spatial scale (Bex, 2010). This relationship has not been established for letters, but we hypothesize that the impact of visual distortion on letter acuity will also depend on the spatial scale of distortions.

Although the effect of spatial distortion on letter acuity has not yet been studied, other work has examined the spatial scale at which letters are identified. Solomon and Pelli (1994) used a critical band noise-masking paradigm in which contrast thresholds for letter identification were measured as a function of the spatial frequency (SF) of band-pass filtered noise masks that overlaid the letters (Solomon & Pelli, 1994). They found that, over a broad range of letter sizes, noise masks with peak SF between 3–6 cycles per letter (CPL) impaired letter identification more than masks at other SFs. They therefore proposed that letter recognition is constrained by a single channel (spanning a relatively narrow range of SFs), and identification can be explained with a minimal model consisting of a simple linear filter followed by a nonlinear decision stage. Majaj, Pelli, Kurshan, and Palomares (2002) extended Solomon and Pelli’s work to letters of different sizes and fonts with different types of SF band-pass filtered noise and confirmed letter identification is a bottom-up process determined by a single channel. Based on differences in the SF tuning of masking, they concluded that large letters are identified by their edges and small letters by their constituent strokes (Majaj et al., 2002).

In the present study, we consider how letter identification depends on the scale of spatial distortion and, by extension, on the scale of metamorphopsia. We hypothesize that letter identification will depend on the spatial scale of distortion, as it depends on the spatial scale of masking noise. We are also particularly interested in the relationship between the scale of distortion and the size of the letter. An interaction between the scale of distortion and letter size would have significant implications for the use of acuity to track the progression of structural changes in the retina. Any structural change that modifies the spatial scale of distortion could improve or worsen acuity, depending on this interaction. This would have implications for both the use of acuity as an outcome measure in clinical trials and for the utility of magnification for people with low vision.

### Methods

#### Observers

Two authors (EW and PB) and four naive observers completed a letter identification task. The mean age was 32 years and the age range was 20–47. All observers had normal or corrected acuity and completed the experiment binocularly, except for PB who completed the task monocularly. All procedures adhered to the tenets of the declaration of Helsinki and were approved by an Institutional Internal Review Board.
Stimuli

Stimuli were displayed on a 23-in. (52.5 × 29 cm) HP TouchSmart LCD display (Hewlett-Packard Company, Palo Alto, CA) at a resolution of 1920 × 1080 pixels and refresh rate of 60 Hz. The display was viewed at five different distances—37, 75, 150, 300, or 600 cm—in a dark room. The distortion of the letters and presentation of stimuli were controlled using custom software with Psychtoolbox (Brainard, 1997) in Matlab.

The stimuli comprised a set of 26 uppercase black Sloan letters that spanned 128 × 128 pixels and were generated as described in Shah, Dakin, Redmond, and Anderson (2011). Although letter confusions vary among letters, we selected the full alphabet instead of a subset of 10 letters to reduce the probability of a correct guess and to avoid repressing for responses that were not in the set. The letters were centered in a 768 × 768 pixel (53 cd/m²) gray background. Distortions were created using spatially band-pass filtered noise, similar to methods previously applied to natural scenes (Bex, 2010). Specifically, a pair of SF band-pass filtered Gaussian noise images were used to generate a spatial pattern of pixel-by-pixel shifts in the x and y positions of the pixels in the source image. This procedure produces systematic spatial distortions in the source image on a scale controlled by the filtered noise without affecting the contrast of the image.

The SF band-pass filtered noise was generated using a log exponential digital filter.

\[ A(\omega) \exp \left( -\frac{1}{\ln(\omega / \omega_{\text{peak}})^3/\ln 2} \right) \]

where \( \omega \) is SF and \( b \) is the bandwidth of the filter in octaves which was fixed at one octave. The peak SF of the filter, \( \omega_{\text{peak}} \), was 4, 8, 16, 32, or 64 cycles per image. Each trial, two random noise patches, 768 × 768 pixels, were band-pass filtered at the same peak frequency. One noise sample controlled the horizontal pixel shifts and one controlled the vertical pixel shifts. Each noise patch was normalized so it had a mean of zero and standard deviation of ±1, and then both were multiplied by one of five different magnitudes, 4, 6, 8, 10, or 14. These scaled noise patterns determined the size of the x- and y-pixel-wise shifts using MatLab’s function interp2() to produce distortion in the horizontal and vertical directions. This process produced letter images distorted at peak frequencies of 0.67, 1.33, 2.67, 5.33, or 10.67 CPL. Subjectively, lower SF mainly altered the larger strokes of the letter, while higher distortion frequencies mainly affected the edges of the letters. Unlike Gaussian blurring, the scattering caused by high distortion frequencies tends to increase the contrast at high spatial frequencies (Bex, 2010, figure 2d) rather than decreasing. Figure 1 shows an example of letters distorted with this process. Letter size decreases down the figure, distortion SF increases across the figure, and distortion magnitude is fixed at 10 and 14 pixels in each panel of this illustration. Letters in the rightward bowed middle band of the figure are most difficult to recognize, showing that identification depends on an interaction between letter size, distortion frequency, and distortion magnitude.

Each participant completed three sessions at each of the five viewing distances (performed in random order). At each viewing distance, five distortion frequencies and five distortion magnitudes were presented four times. This generated 100 trials per session and 12 trials per condition across the three sessions per viewing distance.

Procedure

The participants were seated at the required viewing distance with their heads stabilized by a chin rest. At
the start of each trial, the participant fixated a white (153 cd/m²) central point on the screen on a gray background (53cd/m², to match the background of the letters). The participant initiated the trial by pressing the space bar. Next, a randomly selected Sloan letter that was distorted as described above was presented for 100 ms with abrupt onset and offset. Filter frequency and magnitude were pseudo-randomly interleaved within the session according to the method of constant stimuli that generated four trials for each of five distortion frequencies and five distortion magnitudes at each viewing distance.

The participant reported the identity of the letter (26 AFC), guessing if necessary, using a standard computer keyboard. Feedback was provided by turning the fixation point green or red for a correct or incorrect response, respectively. Prior to formal data collection, all participants completed 300 training trials at a 300-cm viewing distance for a subset of 10 Sloan letters (CDHOKNRSVZ). After training, each observer completed the three 100-trial sessions (with all 26 letters) at each of the five viewing distances in a randomized order to limit any learning effect. This resulted in 12 total trials for each unique viewing distance, distortion frequency, and distortion magnitude combination. Data were stored for offline analysis.

Results and discussion

Figures 2A and B show percent correct letter identification (for the 12 trials per condition) as a function of distortion SF, distortion magnitude, and target letter size. Data are shown as 10 maps, with blue corresponding to better and red to worse performance. All observers showed a similar pattern of results, including the monocular and binocular subjects, and so we have collapsed data across all observers. Figure 2A shows the data for each of the five distortion magnitudes with each map showing data plotted as a function of frequency of distortion (CPL) versus letter size (degrees of visual angle). A U-shaped function emerged that is similar to the function observed for letter contrast identification in band-pass filtered noise (Majaj et al., 2002; Solomon & Pelli, 1994). Performance was lowest at distortion SFs of 2.67 CPL and the effect was greatest for smaller letter sizes. Figure 2B shows the same data from the five letter size conditions plotted as a function of distortion SF against distortion magnitude (pixel shift expressed as a percentage of letter size). A similar U-shaped pattern emerged, with the greatest effect evident at highest distortion magnitudes and smaller letter sizes.

Next, we used the viewing distance from each session to convert distortion SF from CPL to cycles per degree (CPD), and distortion magnitude was converted from percentage of letter size to degrees of visual angle. Figure 3 shows the percentage of correct letter identifications across all five covariates (letter size, SF of distortion in CPD or CPL, magnitude of distortion in degrees of visual angle, or percent of letter size), when pooled across all remaining covariates and all participants. The different colors of Figures 3B through D indicate different letter sizes. Figure 3A shows that identification monotonically increased with letter size, with a plateau for letters subtending around 1.3°. There was a parabolic dependence on distortion SF expressed in either CPL (Figure 3B) or CPD (Figure 3C) that, when collapsed across all letter sizes, dips at the 2.67
CPL and 4.0 CPD points, respectively, similar to the U-shaped heat maps depicted in Figure 2. This observation is in contrast to the effect of blur on letter identification, where increasing the scale of blur monotonically reduces acuity as a function of the low pass filter cut-off (Johnson & Casson, 1995).

Figure 3D and E shows a linear relationship between magnitude of distortion and percent correct. A Pearson correlation showed magnitude of distortion (% of letter size) was significantly negatively correlated with performance when collapsed across all letter sizes ($r = -0.67, p < 0.01$). An analysis of variance showed performance did not significantly differ across all six observers for all parameters ($p > 0.5$).

The data in each plot in Figure 3 were fit with a generalized linear model with a logit link function. Stepwise regression analysis using Akaike’s information criterion (AIC) was used to determine which of the three experimentally manipulated covariates (letter size, SF, and magnitude of distortion) were significant for predicting performance. The final model predictors included log transformation of letter size and SF of distortion, magnitude of distortion, participant ID, nonlinear terms for both letter size and SF, and interaction terms between letter size and SF. The model has a McFadden (1974) pseudo $R^2$ of 0.71. The Hosmer-Lemeshow test (Hosmer & Lemeshow, 2004) showed no lack of model fit ($p = 0.99$). We used 10-fold cross-validation to verify the model was not over fit using

Figure 3. Performance (% correct) as a function of the five covariates, (A) letter size, (B) distortion SF in CPL, (C) distortion SF in CPD, (D) magnitude as a percent of letter size, and (E) magnitude in degrees. The individual data points in each plot are mean data collapsed across all observers, and error bars show 95% confidence intervals on the mean from a 1,000 sample bootstrap. The x-axis is log scaled in A–C. Curves show the fit of a generalized linear model, and corresponding bands represent the 95% confidence intervals for the predicted estimates using the model. Colors in B–D indicate letter size as shown in the caption.
CVglm() from the DAAG package in R (Maindonald & Braun, 2014). We assumed the interaction term between object SF (CPL) and letter size (i.e., viewing distance) was representative of retinal SF in terms of CPD, and the interaction term between magnitude of distortion as percentage of letter and letter size represented a term for magnitude of distortion in degrees of visual angle. The interaction between CPL and letter size was a significant predictor in the logistic regression model. This leads us to conclude that the effect of SF of distortion is dependent on viewing distance.

To more closely examine the interaction between letter size and distortion SF, we estimated the distortion SF that led to poorest performance at each letter size. The upper panel shows distortion SF plotted in terms of CPL, and the lower panel is plotted in terms of CPD. The curve is fit using a basic quadratic formula.

Figure 4. Distortion SF causing maximum identification errors at each letter size tested. The upper panel shows distortion SF plotted in terms of CPL, and the lower panel is plotted in terms of CPD. The curve is fit using a basic quadratic formula.

General discussion

Letter identification is a primary performance measure in basic and clinical vision science. Many visual pathologies and image transformations lead to a physical or perceptual spatial distortion of images, but little is known about how this influences letter identification. We therefore examined the effects of spatial distortion on letter identification by manipulating two parameters (SF and magnitude of distortion) to distort 26 Sloan letters with a pixel-remapping algorithm and measured this transformation on letter identification. With this parameterized distortion, we measured letter recognition performance as a function of letter size, SF of distortion, and magnitude of distortion.

As expected, letter identification errors increased with decreasing letter size and increasing magnitude of distortion (Figure 3A, D, and E). Performance was best for letters that spanned 1.3 degrees of visual angle (approximately 20/300 acuity). We found a nonlinear dependence of performance on SF of distortion and observed an interaction with SF and size of letter (Figure 4). A predictive generalized linear model confirmed the interdependence between SF and letter size. This finding has significant implications for the assessment and monitoring of clinical populations affected by both acuity loss and metamorphopsia.

We analyzed the SF tuning of distortion two ways, both in terms of the number of cycles per object and in terms of the number of CPD of visual angle. A nonlinear, quadratic-shaped function described performance as a function of the SF of distortion (Figure 3B and C). When considering CPL, i.e., object SF, we found that performance was worse at higher spatial frequencies for larger letters and lower SFs for smaller letters (Figure 4). This pattern is comparable to previous findings measuring contrast sensitivity for varying letter sizes and object SFs. Alexander, Xie, and Derlacki (1994) found highest sensitivity occurred at higher SFs for larger letters and at lower SFs for smaller letters. Additionally, Majaj et al. (2002) measured letter identification in noise masks as a function of SF and reported that large letters are identified by high SF edges, while smaller letters are identified by large gross strokes. In the present study, distortion at high object SFs resulted in worse performance for larger letters, consistent with these studies. Collectively, these data suggest that our visual system uses high SF information for large letter identification and is unable to appropriately use such information when it is spatially distorted.

The dip in letter identification performance across object SF ranged from approximately 2.3 to 6 CPL, depending on the size of the letter, with an average minimum at 3.17. This is in agreement with previous
reports that letter identification was mediated by a single channel tuned at 3 CPL (Solomon & Pelli, 1994). A similar single channel mediated tuning has been reported for face recognition, where 8.8–17.5 cycles per face was found to be optimal for face recognition (Gold, Bennett, & Sekuler, 1999). We speculate that spatial distortions may play an analogous role in face perception and may be related to reports of impaired face recognition in patients with AMD who also experience metamorphopsia (Bullimore, Bailey, & Wacker, 1991; Tejeeria, Harper, Artes, & Dickinson, 2002).

When we considered SF of distortion in terms of cycle per degree, or retinal SF, we found the opposite pattern; performance was worse for larger letters at lower SFs and smaller letters with high SF distortion. We speculate that this is due to an interaction between the SF content of letters of differing size and the contrast sensitivity function of the visual system. We assume that minimum letter recognition performance corresponds to highest sensitivity at a particular SF, essentially creating a piecewise inverted contrast sensitivity function in Figure 3C. When all local minima are averaged across all letter sizes, we find lowest performance (i.e., peak sensitivity) to be 3.26 CPD, similar to peak sensitivity measured on the contrast sensitivity function, 2.97 CPD (Watson, 2000). This is also similar to a 4 CPD peak sensitivity to distortion reported by Bex (2010) when considering a similar manipulation of distortion in natural images.

It has been argued that the presence of clinical visual distortion in retinal disease is caused by a spatial disturbance in the photoreceptor layer that can result in both a loss of visual acuity and the presence of visual distortion (Jensen & Larsen, 1998; Morris, Imrie, Armbrrecht, & Dhillon, 2007). There are many important differences between the distortions simulated in the present study and those experienced by patients with macular disease. For example, the distortions simulated in the present study were the same binocularly, whereas pathological distortions would differ between eyes. Furthermore, we recently reported that monocular distortions can be suppressed by a healthy eye (Wiecek et al., 2014), so impairments like those reported here may only be manifest with monocular testing. Our simulated distortions were fixed on screen and changed between trials, whereas pathological metamorphopsia would move with eye position, and it is possible that observers might adapt to distortion, as has been demonstrated in prism adaptation studies (Helmholtz, 1924). Nevertheless, while we address those questions in ongoing studies, we hypothesized that it may be possible to relate the SF and magnitude of distortion to pathological changes at the retinal level. For example, a patient with intermediate dry macular degeneration may have large drusen spanning approximately 125 μm (Bird et al., 1995; Ferris et al., 2005). Distortions at this spatial scale correspond to a displacement of approximately 0.44 degrees of visual angle (Curcio & Allen, 1990). Depending on the spacing of individual druse, this could correspond to a frequency of displacement around 2 CPD. In our study, spatial distortions at this scale maximally impaired identification of letters subtending around 1.34 degrees of visual angle, which would correspond to an acuity of approximately 20/160 at a viewing distance of 3 m. Additionally if one considers the height of an average druse in relationship to the magnitude of spatial distortion, one large druse of approximately 72 μm (Sadigh et al., 2013) corresponds to 0.26 degrees of visual angle. In the present study, a 0.26° shift of spatial distortion was shown to impair letter recognition with letter sizes of 0.67° (Figure 3E).

Manipulating viewing distance rather than the physical size of the letter allowed us to consider two distortion parameters (magnitude and frequency) in both image space and retinal space. With a logistic regression model, we found that there was an interaction between viewing distance (i.e., letter size) and SF of distortion for predicting performance. This means that distortion that originates the retina will have differential impact on performance depending on viewing distance. For example, a stable distortion (retinal space) may only affect acuity or reading performance at certain letter sizes, while other letter sizes may remain unaffected. Thus, it is possible that a patient may experience distortions that impair the identification of large letters, with little or no effect on identification of small letters. Such a case can be demonstrated in Figure 1—large and medium sized letters in the center of the image are more difficult to identify than smaller letters below them even though the SF and magnitude of distortion are constant. This observation may be directly related to clinical reports of retinal disease patients who are able to read small but not large text. It has been assumed that this phenomenon occurs due to the presence of fovea-sparing ring scotomas (Sunnness, Rubin, Zuckerbrod, & Applegate, 2008). The present data suggest metamorphopsia may also contribute to this phenomenon.

Our findings may therefore have implications for understanding concomitant acuity loss and metamorphopsia. Since acuity is used as a primary outcome measure, it is important to bear in mind that letter identification errors may depend on the scale and SF of retinal distortions. For example, an improvement or a reduction in letter recognition performance (visual acuity) could occur with either a progression of remediation of metamorphopsia. Similarly, our results may also have implications for low vision rehabilitation because magnification is often a useful tool for these patients. Our data suggest that the optimal magnifica-
tion may depend on the level of metamorphopsia as well as viewing distance and task. For example, face recognition or watching television may have a different optimal magnification than reading text at arms length. It is possible that the present data provide a principled approach for computing optimal magnification.

Conclusions

Visual acuity is widely used as a measure of performance in basic and clinical vision science, yet the impact of spatial distortions on this measure is largely unknown. Our data show that letter recognition performance peaks at a letter size of approximately 1.3° and decreases with increasing magnitude of distortion. SF of distortion does not linearly scale with performance. Instead, it is tuned to specific channels at varying letter sizes, which has clinical implications when using acuity as an outcome measure for patients who also experience visual distortion. We found that retinal SF affects distortion at midrange frequencies and can be explained with the tuning of a basic contrast sensitivity function, while object centered SF distortion follows a similar pattern of letter object recognition sensitivity and is tuned to approximately 3 CPL, depending on the size of the letter.

Keywords: letter recognition, visual acuity, spatial vision, metamorphopsia, clinical vision, macular degeneration

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