Vision Research 105 (2014) 86–91

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The effect of exposure duration on visual acuity for letter optotypes and gratings

J. Jason McAnany *

Department of Ophthalmology and Visual Sciences, University of Illinois at Chicago, 1855 W. Taylor St., Chicago, IL 60612, USA
Department of Psychology, University of Illinois at Chicago, 1007 W. Harrison St., Chicago, IL 60612, USA
Department of Bioengineering, University of Illinois at Chicago, 851 South Morgan St., Chicago, IL 60607, USA

ARTICLE INFO

Article history:
Received 3 April 2014
Received in revised form 26 August 2014
Available online 2 October 2014

Keywords:
Visual acuity
Letters
Gratings
Object frequency

ABSTRACT

This study compared the effects of exposure duration on letter and grating targets in a visual acuity (VA) task and determined if the broadband nature of letters accounts for their temporal summation characteristics. Log MAR (minimum angle of resolution) VA of five individuals (ages 25–36) was measured with a set of tumbling E optotypes for durations of 24 ms to 1 s. The Es were either unfiltered or low-pass filtered to determine the object frequencies (cycles per letter; cpl_E) mediating VA. The retinal frequencies mediating VA for the unfiltered E (cycles per degree; cpd_E) were derived from the ratio of cpl_E to MAR. Values of cpd_E were compared to threshold retinal frequency obtained with band-limited Es and gratings to further evaluate the effects of stimulus bandwidth. Both log MAR and log cpl_E for the unfiltered E decreased as duration increased up to approximately 260 ms, and were constant thereafter. VA also improved for gratings and band-pass filtered Es, but over a shorter time course (approximately 150 ms). The effect of duration on VA for the broadband E, Gabor, and band-pass filtered E was similar when the object frequencies mediating VA were included in the definition of VA by converting to cpd_E. The results indicate that the pattern of temporal integration for the tumbling E is related to its broadband nature. Band-pass filtered letters can simplify the interpretation of VA because the object frequency information mediating VA is known exactly and is independent of duration and letter size.

1. Introduction

Visual acuity (VA) for letter optotypes and grating targets improves with increasing exposure duration until the “utilization time” is achieved, which is defined as the termination of temporal integration (Kietzman & Gillam, 1972; Piéron, 1952). The utilization time measured with standard letter optotypes can be several hundred milliseconds (Alexander et al., 1993; Baron & Westheimer, 1973; Ng & Westheimer, 2002; Niwa & Tokoro, 1997). Although there has been minimal research examining the effect of duration on grating VA, the few studies that have been undertaken suggest that the utilization time for gratings is relatively short compared to letters (Graham & Cook, 1937; Keesey, 1960). Several factors have been proposed to account for the long utilization times recorded for letter VA tasks, but the explanation is not entirely clear (Baron & Westheimer, 1973; Heinrich, Kruger, & Bach, 2010; Ng & Westheimer, 2002).

One possible explanation for the apparent differences in utilization time for letter and grating VA may be related to differences in the object frequency content of letters and sinewave gratings. As discussed elsewhere (Anderson & Thibos, 1999), the Fourier spectra of standard letter optotypes contain a broad range of object spatial frequencies (designated in cycles per letter; cpl), orientations, and phases, which is unlike sinusoidal grating stimuli. Reducing letter size shifts the frequency spectrum of the letter to higher retinal frequencies (cycles per degree; cpd). For small letters, the high-frequency optical and neural limits of resolution are surpassed and VA must then be based on the remaining lower object frequency components (corresponding to lower retinal frequencies). Sensitivity to the different object frequencies contained in the letter may be dependent on duration. For example, for long (or unlimited) exposure durations, the subject may have sufficient time to make use of the low object frequencies, which contain relatively little information regarding letter identity or orientation. Despite the minimal information conveyed by low object frequencies, these frequencies correspond to low retinal frequencies, which permits the identification of small letters (e.g. smaller than the stroke width of the letter). For brief exposure durations,

* Address: Department of Ophthalmology and Visual Sciences, University of Illinois at Chicago, 1855 W. Taylor St., Chicago, IL 60612, USA.
E-mail address: jmcana1@uic.edu

http://dx.doi.org/10.1016/j.visres.2014.08.024
0042-6989/

however, sensitivity to low object frequencies may be poor, requiring the use of high object frequencies that convey reliable letter identity or orientation information. The ability to use different object frequency components is not possible for narrowband sinewave gratings, which may account for the utilization time differences between letters and gratings.

The purpose of the present study was to compare the effects of exposure duration on letter and grating targets in a VA task and determine if the broadband nature of letters accounts for their temporal summation characteristics. VA was measured across a range of durations for a standard tumbling E target to determine the utilization time. At each duration, the object frequencies mediating VA for the E were derived using an established approach (Anderson & Thibos, 1999, 2004; McAnany et al., 2011). Specifically, the E was successively filtered with Gaussian low-pass filters until VA was affected, under the assumption that if the removal of specific high object frequencies impaired VA, then those frequencies must be necessary for the task. To examine further the effect of the broadband nature of the E on VA, VA was also measured as a function of duration for Gabor patches (Gaussian-windowed sinewave gratings) and band-pass filtered Es, which are both narrow-band in object frequency content.

2. Methods

2.1. Subjects

Five normally-sighted individuals (3 males and 2 females, ages 23–36 years) participated in the study. Each subject had normal distance visual acuity as assessed with ETDRS charts and normal contrast sensitivity as assessed with Pell-Robson charts. The study conformed to the Code of Ethics of the World Medical Association (Declaration of Helsinki) and the experiments were approved by an institutional review board at the University of Illinois at Chicago. Written informed consent was obtained from each subject prior to testing.

2.2. Instrumentation

The instrumentation has been described in detail elsewhere (McAnany et al., 2011). In brief, stimuli were generated by a Macintosh G4 computer and were displayed on an NEC monitor (FE2111SB) with a resolution of 1024×768 and an 85-Hz refresh rate. The display monitor, which was the only source of illumination in the test area, was viewed in a front-surface mirror to achieve a 9 m test distance. The stimulus display was viewed monocularly through a phoroptor with the subject's best refractive correction. Experiments were written in Matlab using the Psychophysics Toolbox extensions (Brainard, 1997).

2.3. Stimuli

Three types of test stimuli were used: standard tumbling Es, Gabor patches, and band-pass filtered tumbling Es. The standard tumbling Es were constructed according to the principles of the Sloan font (NAS-NRC, 1980), such that the stroke width was one fifth of the overall optotype size and the three bars were of equal length. For the unfiltered Es, log MAR was based on the stroke width, per convention. Low-pass filtered Es were created by convolving the standard unfiltered E with 2D low-pass Gaussian functions of 4 different standard deviations (σ_{stim}): 0.0 (unfiltered), 0.2, 0.8, and 3.2 arcmin. The low-pass filtered Es were used in the experiments that determined the object frequencies mediating VA for the unfiltered E, as discussed below. The band-pass filtered E was constructed by filtering the standard E with a cosine log filter (Chung & Tjan, 2009; Peli, 1990). The filter gain (G) at frequency (f) is given by:

$$G(f) = 1/2\left[1 + \cos\left(\pi\frac{\log(f)\log(p)}{\log(c)\log(p)}\right)\right], \quad (1)$$

where p is the center frequency of the filter, and c is the cut-off frequency at which the amplitude of the filter is zero. In the present study, the cosine log filter had a center frequency of 2.5 cpl and a bandwidth of one octave. A peak object frequency of 2.5 cpl was selected to match the object frequency corresponding to the stroke width of the E, given that there are five strokes in each letter and two strokes (one light bar and one dark bar) per cycle. For the low-pass and band-pass filtered Es, log MAR was based on the stroke width of the original unfiltered E.

The Gabor patch consisted of a sinewave grating convolved with a circular Gaussian window that had a space constant that was proportional to the grating period, such that there were three cycles available in the Gaussian window for all spatial frequencies (sizes). The Gabor patches were presented in sine phase and had a spatial frequency bandwidth of approximately one octave at half-height. For Gabor patches, the definition of log MAR was based on half of the Gabor patch period, which is equivalent to one dark bar or one light bar. This definition was used to maintain consistency with the definition of log MAR used for the Es and is the basis for the standard assumption that a 30 cpd grating is equivalent to 0 log MAR (Regan et al., 1981).

Stimuli were presented at durations ranging from 24 ms to 1 s in 13 steps spaced approximately 0.15 log units apart. The targets were presented at the center of an adapting field that subtended 3.4° horizontally and 2.6° vertically. The luminance of the adapting field was 90 cd/m^2 and the luminance of the unfiltered E was 1.0 cd/m^2, yielding a Weber contrast of −99%. For the Gabor patches and band-pass filtered Es, the luminance of the adapting field was 40 cd/m^2. The contrast of the low-pass and band-pass filtered Es was defined relative to the original E from which they were derived, without rescaling, such that the filtered images were considered to have Weber contrasts of −99%. The Gabor patches also had a Weber contrast of 99%. The stimulus luminances were verified with a photometer (Minolta LS 110) and the temporal characteristics of the display were confirmed using an oscilloscope and photocell.

2.4. Procedure

The same two-alternative forced-choice staircase procedure was used to measure log MAR VA for each stimulus type. The subject's task was to judge the orientation of the tumbling E (right vs up) or the Gabor patch (horizontal vs vertical). A brief warning tone signaled the start of each stimulus presentation, and the subject verbally reported the orientation, which was recorded by the examiner. The subjects were given practice trials to become familiar with the task. An initial estimate of log MAR was obtained by presenting the target at a suprathreshold size and then decreasing the size by 0.1 log unit until an incorrect response was recorded. Following this initial search, log MAR was determined using a two-down, one-up decision rule, which provides an estimate of the 71% correct point on a psychometric function (Garcia-Perez, 1998; Levitt, 1971). Each staircase continued until 10 reversals had occurred, and the mean of the last 6 reversals was taken as log MAR.

3. Results

Fig. 1 plots mean log MAR for the unfiltered E (squares) and the Gabor patch (circles) as a function of log exposure duration for the

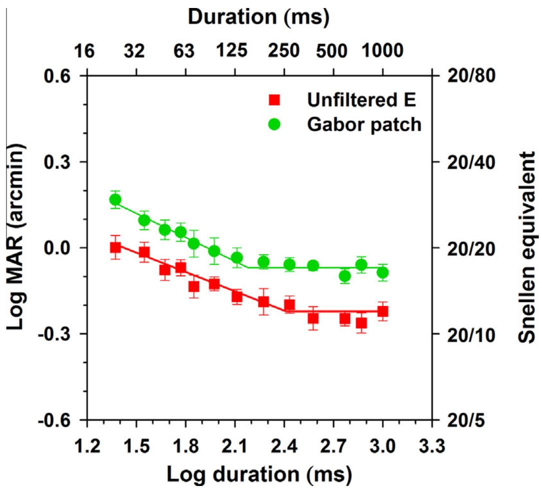

Fig. 1. Mean log MAR (±1 SEM) as a function of log stimulus duration measured with unfiltered Es (squares) and Gabor patches (circles). The right *y*-axis shows the Snellen equivalents of the log MAR values and the top *x*-axis shows the linear values of duration. The solid lines are the least-squares best-fits of the two-limbed function described in the text.

five subjects. Error bars represent ±1 standard error of the mean (SEM). Threshold letter size decreases (retinal frequency increases) toward the bottom of the vertical scale and the right *y*-axis shows the corresponding Snellen equivalents of the log MAR values. The data were fit piecewise with two linear segments: the slope of the descending segment was unconstrained, whereas the slope of the second segment was set to zero. Log MAR improved linearly by approximately 0.25 log units for both targets, but the utilization time and slopes differed. Specifically, log MAR for the unfiltered E improved up to 260 ms (slope of −0.15), whereas log MAR for the Gabor patch improved up to 153 ms (slope of −0.28).

The object frequency information mediating VA for the unfiltered E for each exposure duration was derived using an approach described previously (Anderson & Thibos, 1999, 2004; McAnany et al., 2011). In brief, log MAR was measured for tumbling E optotypes that were convolved with low-pass filters of different cutoff frequencies. The object frequencies mediating VA for the tumbling E were derived from the relationship between log MAR and log σ_{stim} as follows. First, log MAR was plotted as a function of log σ_{stim} and the data were fit with the log form of the following equation (Levi & Klein, 1990):

$$\mathrm{MAR} = \mathrm{MAR}_{\mathrm{Unfiltered}}\left(1 + (\sigma_{\mathrm{stim}}/\sigma_{\mathrm{int}})^2\right)^{1/2}, \quad (2)$$

where $\mathrm{MAR}_{\mathrm{Unfiltered}}$ is VA for the unfiltered E ($\sigma_{stim} = 0$) and σ_{int} is the value of σ_{stim} that increases log MAR by 0.15 log units ($\log\sqrt{2}$) above log $\mathrm{MAR}_{\mathrm{Unfiltered}}$. The value of σ_{int} (arcmin) was used to estimate the *effective* object frequencies used to perform the task (cycles per letter; $\mathrm{cpl_E}$) as follows:

$$\mathrm{cpl_E} = 5 * \mathrm{MAR}_{\mathrm{Unfiltered}} * 1/(2\pi * \sigma_{int}). \quad (3)$$

The value of $\mathrm{cpl_E}$ provides an index of the lowest effective object frequency that can be used for orientation judgments of the tumbling E. The logic underlying this approach is that if selectively removing frequencies from the E by low-pass filtering does not affect VA, then those frequencies were not useful for performing the task. Conversely, if selectively removing a range of frequencies from the E impairs VA, then those frequencies were useful for performing the task. Thus, by examining the relationship between log MAR and log σ_{stim}, the object frequencies necessary to perform the VA task can be derived.

A measure of the effective retinal frequency ($\mathrm{cpd_E}$) mediating VA for the unfiltered E was derived from $\mathrm{MAR}_{\mathrm{Unfiltered}}$ and $\mathrm{cpl_E}$ using the following relationship:

$$\mathrm{cpd_E} = 12 * \mathrm{cpl_E}/\mathrm{MAR}_{\mathrm{Unfiltered}}. \quad (4)$$

The value of $\mathrm{cpd_E}$ provides a measure of VA that accounts for both the letter size at threshold and the effective object frequencies mediating VA. If $\mathrm{cpl_E}$ is equal to 2.5, then Eq. (4) gives the standard nominal transform between retinal frequency and letter size (i.e. 30 cpd is equivalent to 0 log MAR). The advantage of the present approach is that $\mathrm{cpl_E}$ is measured and used in the definition of effective retinal frequency ($\mathrm{cpd_E}$), so that no assumption of object frequency is needed in the specification of VA.

Fig. 2 presents mean log MAR as a function of log σ_{stim} (i.e. the cutoff frequency of the low-pass filter) for the five subjects (±1 SEM). Data for exposure durations ranging from 24 ms to 129 ms are shown in the upper panel and data for exposure durations ranging from 188 ms to 1 s are shown in the lower panel. For reference, the right *y*-axis shows the corresponding Snellen equivalents of the log MAR values. The curves are the least-squares bests fit of Eq. (2) to the data. According to Eq. (2), log MAR is approximately constant for small values of log σ_{stim}, whereas log MAR increases linearly with a slope of 1 for substantially larger values of log σ_{stim}. This pattern was observed for each exposure duration. Fig. 2 shows that log MAR improved with increasing duration for each value of σ_{stim}, but the amount of improvement was somewhat greater for the unfiltered and minimally filtered Es, compared to the most filtered E. The knee points of the curves are shifted minimally, resulting in a greater vertical than horizontal shift with temporal extent.

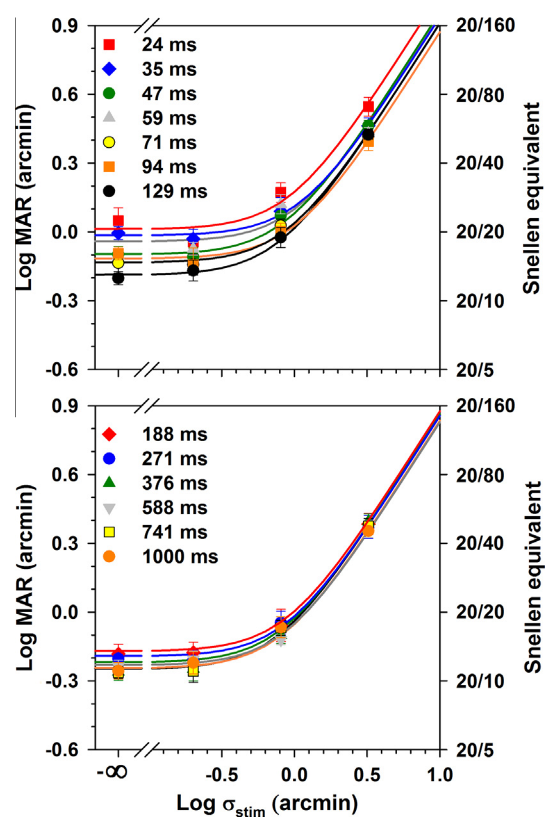

Fig. 2. Log MAR (±1 SEM) as a function of log σ_{stim} measured at each stimulus duration. The upper panel shows data for the seven shortest durations, whereas the lower panel shows data for the six longest durations. The right *y*-axes show the Snellen equivalents of the log MAR values. The solid lines represent the least-squares best-fits of Eq. (2) to the data.

Fig. 3 plots mean log MAR for each of the four σ_{stim} values for the five subjects (±1 SEM). The right *y*-axis shows the corresponding Snellen equivalents of the log MAR values. The data were fit with the same function used to describe the data in Fig. 1. The data for $\sigma_{stim} = 0.0'$ (i.e. log $MAR_{Unfiltered}$) are replotted from Fig. 1 for comparison. For the three lowest blur values ($\sigma_{stim} = 0.0'$, $0.2'$, $0.8'$), the utilization times were similar (approximately 260 ms). However, for the most blurred E, the utilization time was substantially longer (573 ms). Increasing duration improved log MAR by approximately 0.25 log units for the three lowest σ_{stim} values, but the improvement was less (approximately 0.14 log unit) for the highest σ_{stim} value. Thus, the utilization time was relatively long and the amount of VA improvement was relatively small when the high object frequencies (edges) were removed from the E.

The object frequencies mediating VA at each duration for the unfiltered E were derived from Eq. (3), based on the data shown in Fig. 2. The relationship between log effective object frequency (cpl_E) and log exposure duration is shown in Fig. 4. In this figure, mean log cpl_E is plotted as a function of log exposure duration for the five subjects (±1 SEM). The horizontal dashed line represents the expected result if a constant object frequency range (centered at 2.5 cpl) mediates VA for all exposure durations. The value of 2.5 cpl corresponds to the stroke frequency of the E. Clearly, the results do not conform to this expectation. Rather, log cpl_E decreased linearly (slope of 0.12) by 0.13 log units as log duration increased. The time course of the change in log cpl_E (utilization time of 305 ms) was similar to the time course of the change in log MAR for the unfiltered E (260 ms). The results indicate that the information mediating VA depends on duration, with subjects using lower object frequencies at longer durations. Note that the vertical placement of the function in Fig. 4 depends on the point selected on the log MAR vs log σ_{stim} function (Fig. 2). Selecting a lower point on the curve would result in higher estimates of cpl_E, which would more closely match the object frequency values reported previously (Alexander & McAnany, 2010; Anderson & Thibos, 1999). However, selecting a different point on the log MAR vs log σ_{stim} curve would not affect the shape of the log cpl_E vs log duration function; object frequency changes with duration regardless of the point that is selected as the basis for deriving object frequency.

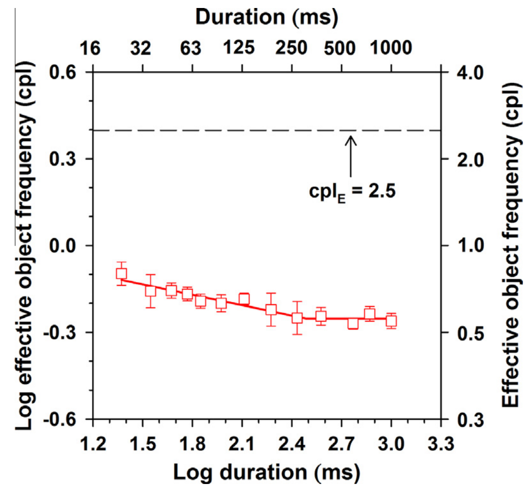

Fig. 4. Mean log object frequency (cpl_E) as a function of log stimulus duration for the five subjects (±1 SEM). The right *y*-axis shows the linear values of cpl_E and the top *x*-axis shows the linear duration values. The solid line is the least-squares best-fit of the two-limbed function described in the text. The dashed line represents the expected results if a constant range of object frequencies centered at 2.5 cpl mediates VA.

In Fig. 5, mean (±1 SEM) log effective retinal frequency (cpd_E) for the unfiltered E (squares) is plotted as a function of log exposure duration for the five subjects. These data were derived from Eq. (4). As in Fig. 4, the vertical placement of the cpd_E function depends on the point selected on the log MAR vs log σ_{stim} function for the calculation of object frequency. Selecting a lower point on the curve would shift the log cpd_E vs log duration function vertically downward, but would not affect the shape of the function. The Gabor patch data (circles) are replotted from Fig. 1 in units of cpd. Mean log retinal frequency (±1 SEM) as a function of log duration is also shown for band-pass filtered Es (triangles). The Gabor patch, band-pass filtered E, and unfiltered E had similar utilization times (153 ms, 134 ms, and 180 ms, respectively). Restricting the object frequency content by band-pass filtering the E into a one octave wide range of frequencies centered at 2.5 cpl changed the temporal integration characteristics of the

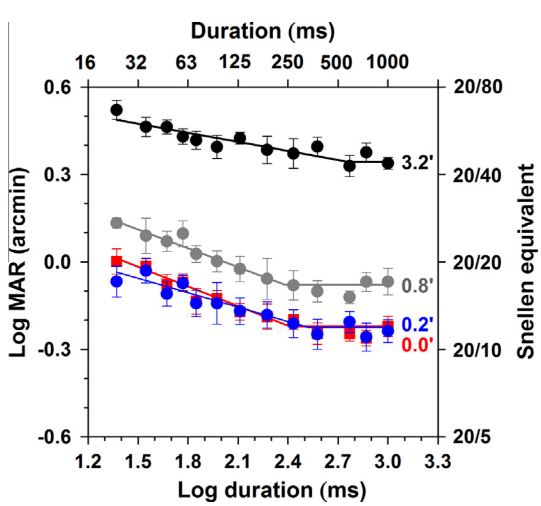

Fig. 3. Mean log MAR (±1 SEM) as a function of log stimulus duration for each level of stimulus blur (shown to the right of each function). The right *y*-axis shows the Snellen equivalents of the log MAR values and the top *x*-axis shows the linear values of duration. The solid lines are the least-squares best-fits of the two-limbed function described in the text.

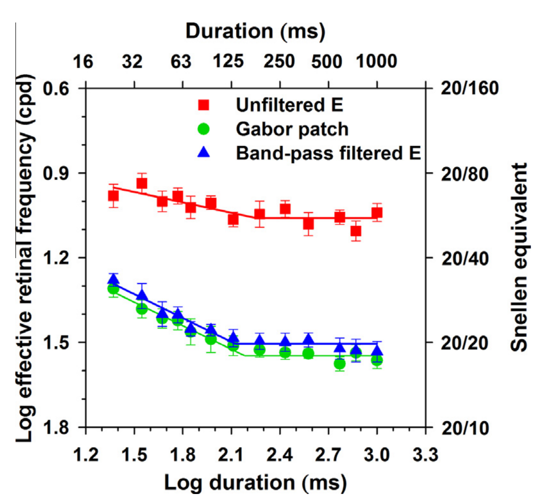

Fig. 5. Mean log effective retinal frequency (cpd_E) for the unfiltered E (squares) as a function of log stimulus duration (±1 SEM). Data for the Gabor patches are also plotted in terms of retinal frequency (cpd). Additionally, log retinal frequency measured with band-pass filtered tumbling Es (triangles) is shown as a function of log duration.

tumbling E, making it appear more like the Gabor patch. Furthermore, accounting for the change in object frequency with duration by plotting the unfiltered E data in terms of cpd_E (Eq. (4)) reduced the utilization time so that it approximated the band-limited Gabor and band-pass filtered E targets.

4. Discussion

This study compared the effects of exposure duration on letter and grating targets in a VA task and evaluated the extent to which the broadband nature of letters accounts for their long utilization time. Log MAR VA for unfiltered tumbling Es improved as duration was increased up to approximately 260 ms and was constant thereafter. This pattern of temporal integration is consistent with that reported previously for broadband letter optotypes (Alexander et al., 1993; Baron & Westheimer, 1973; Ng & Westheimer, 2002; Niwa & Tokoro, 1997). In contrast, log MAR VA for narrow-band Gabor patches had a utilization time that was approximately half of that of the unfiltered E (Fig. 1). When the object frequency information mediating VA for the unfiltered E (cpl_E) was incorporated into the definition of VA by converting from log MAR to log effective retinal frequency (cpd_E), the utilization time was reduced, so that it approximated the Gabor patch and band-pass filtered E functions (Fig. 5). Taken together, these results indicate that the long utilization time for standard letter optotypes (up to approximately 260 ms; Fig. 1) is due, at least in part, to the broadband nature of these targets.

Although letters are broadband in object frequency content, the log MAR VA scale is based on the assumption that a constant narrow band of object frequencies mediates VA for letters at all sizes and durations. That is, log MAR refers to the threshold angular subtense of the "critical detail" of the letter that mediates identification (Bailey & Lovie-Kitchin, 2013). The critical detail for letter optotypes is considered to be the stroke width or the spacing between strokes (gap width) and is assumed to be independent of test parameters such as exposure duration and letter size. However, the results of the present study show that the object frequencies mediating VA can vary with stimulus exposure duration, which can complicate the use of standard letters in VA tasks. As such, it may be useful to consider this complication in the interpretation of other studies using broadband letters.

Although typical clinical measurements of VA do not limit the exposure duration, VA has been measured for briefly presented letter targets in patients with retinitis pigmentosa, central serous retinopathy, macular edema, and glaucoma (Alexander et al., 1993; Kono & Yamade, 1996), and it has been suggested that VA for briefly presented letter optotypes may provide additional important information that is not available from measurements made at unlimited duration (Kono & Yamade, 1996). Consequently, understanding the factors underlying VA for briefly presented letter optotypes has potential clinical relevance for future testing paradigms, particularly if comparisons of VA at short and long durations are made. The present data show that caution may be warranted when comparing VA measurements performed at short durations (less than approximately 250 ms) to those made at unlimited duration, as different object frequency information may mediate these measurements.

The ability to make use of different object frequencies in a VA task, as shown in Fig. 4, allows performance to be optimized over a large range of letter sizes. For example, for large letters, the individual strokes can be resolved and basing judgments on relatively high object frequencies is ideal because these frequencies contain the most reliable letter orientation (or identity) information. For small letters, the individual strokes cannot be resolved, so subjects must base orientation (or identity) judgments on low object frequencies that correspond to features that are larger than the stroke width. The low object frequencies, however, contain less information regarding orientation (or identify) than high object frequencies. Consequently, there is a lower limit on the object frequencies that can mediate performance, as indicated by the constant object frequency range used for durations longer than approximately 300 ms (Fig. 4). Of note, the inability to make use of high object frequencies for small letter sizes is expected to generalize to other optotypes (e.g. Landolt C) and other tasks (e.g. letter identification). Although additional work is needed to determine the effects of task demands, Majaj et al. (2002) showed that similar object frequencies mediate letter identification and N vs Z orientation judgments.

The change in object frequency with exposure duration (Fig. 4) is reminiscent of the change in object frequency with increasing letter size shown in previous studies of letter contrast sensitivity (Chung, Legge, & Tjan, 2002; Majaj et al., 2002; McAnany & Alexander, 2008). For example, Chung, Legge, and Tjan (2002) reported that the log object frequency mediating letter contrast sensitivity increased linearly with log letter size, with a slope of approximately 1/3. The slope of the function relating the log object frequency mediating VA and log exposure duration (Fig. 4) was 0.12, which is less than 1/3. Nevertheless, the pattern is the same as that reported in studies of contrast sensitivity for letters of different size (Chung, Legge, & Tjan, 2002; Majaj et al., 2002; McAnany & Alexander, 2008), in that higher object frequencies mediated performance for larger letters (i.e. high object frequencies were used for brief exposure durations where the letter size at threshold was large).

None of the functions relating log retinal frequency and log duration (Fig. 5) had a slope of −1.0 for the range of durations tested, which would be the expected slope if Bloch's time-intensity reciprocity law accounted for VA as a function of duration. Bloch's law accounts well for the relationship between exposure duration and threshold contrast for short exposure durations (Bartlett, 1965), but it is important to note that present study measured the relationship between exposure duration and VA (i.e. size) for a high contrast target. Consequently, contrast integration over time is unlikely to play a major role in the effect of duration on VA, at least for the durations tested in the present study. Instead, the slope of the high-frequency limb of the contrast sensitivity function (CSF) and the dependence of duration on the high-frequency CSF cutoff is likely to determine the slope of the VA vs duration functions (Fig. 5). That is, measuring high contrast VA at different durations is equivalent to determining the high-frequency cutoff for a series of CSFs obtained at different durations. Consequently, the slope of the VA vs duration function depends on the way in which the high-frequency cutoff of the CSF changes with duration, which explains why Bloch's law did not account for the effect of duration on VA in the present study.

In conclusion, if it is assumed that the object frequencies mediating VA are independent of duration, the present results are consistent with previous studies showing that letter VA has a long utilization time (Alexander et al., 1993; Baron & Westheimer, 1973; Ng & Westheimer, 2002; Niwa & Tokoro, 1997). However, if the object frequencies mediating VA are measured and included in the definition of VA (i.e. cpd_E), rather than assuming a constant range, then VA is weakly dependent on duration, with a relatively short utilization time that approximates that of narrow-band targets. These results suggest that the use of standard letter optotypes, with their broad spatial frequency content, can potentially complicate the interpretation of VA measurements at different stimulus exposure durations. Spatially band-pass filtered letters could alleviate some of the difficulty in interpreting VA as a function of duration, as the object frequency information mediating VA for these targets is known exactly and is independent of duration and letter size.

Acknowledgments

This research was supported by NIH Grants R00EY019510 and P30EY001792 and an unrestricted departmental grant from Research to Prevent Blindness.

References

Alexander, K. R., Derlacki, D. J., Fishman, G. A., & Szlyk, J. P. (1993). Temporal properties of letter identification in retinitis pigmentosa. *Journal of the Optical Society of America A: Optics, Image Science, and Vision, 10*(7), 1631–1636.
Alexander, K. R., & McAnany, J. J. (2010). Determinants of contrast sensitivity for the tumbling E and Landolt C. *Optometry and Vision Science, 87*(1), 28–36. http://dx.doi.org/10.1097/OPX.0b013e3181c61117.
Anderson, R. S., & Thibos, L. N. (1999). Sampling limits and critical bandwidth for letter discrimination in peripheral vision. *Journal of the Optical Society of America A: Optics, Image Science, and Vision, 16*(10), 2334–2342.
Anderson, R. S., & Thibos, L. N. (2004). The filtered Fourier difference spectrum predicts psychophysical letter discrimination in the peripheral retina. *Spatial Vision, 17*(1–2), 5–15.
Bailey, I. L., & Lovie-Kitchin, J. E. (2013). Visual acuity testing. From the laboratory to the clinic. *Vision Research, 90*, 2–9. http://dx.doi.org/10.1016/j.visres.2013.05.004.
Baron, W. S., & Westheimer, G. (1973). Visual acuity as a function of exposure duration. *Journal of the Optical Society of America, 63*(2), 212–219.
Bartlett (1965). Thresholds as dependent on some energy relations. In C. H. Graham (Ed.), *Visual perception* (pp. 154–184). New York: Wiley.
Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*(4), 433–436.
Chung, S. T., Legge, G. E., & Tjan, B. S. (2002). Spatial-frequency characteristics of letter identification in central and peripheral vision. *Vision Research, 42*(18), 2137–2152.
Chung, S. T., & Tjan, B. S. (2009). Spatial-frequency and contrast properties of reading in central and peripheral vision. *Journal of Vision, 9*(9), 11–19. http://dx.doi.org/10.1167/9.9.16 (article no. 16).
Garcia-Perez, M. A. (1998). Forced-choice staircases with fixed step sizes: Asymptotic and small-sample properties. *Vision Research, 38*(12), 1861–1881.
Graham, C. H., & Cook, C. (1937). Visual acuity as a function of intensity and exposure-time. *American Journal of Psychology, 49*, 454–461.
Heinrich, S. P., Kruger, K., & Bach, M. (2010). The effect of optotype presentation duration on acuity estimates revisited. *Graefes Archive for Clinical and Experimental Ophthalmology, 248*(3), 389–394. http://dx.doi.org/10.1007/s00417-009-1268-2.
Keesey, U. T. (1960). Effects of involuntary eye movements on visual acuity. *Journal of the Optical Society of America, 50*, 769–774.
Kietzman, M., & Gillam, B. J. (1972). Visual temporal integration and simple reaction-time. *Perception & Psychophysics, 11*(5), 333. http://dx.doi.org/10.3758/Bf03206263.
Kono, M., & Yamade, S. (1996). Temporal integration in diseased eyes. *International Ophthalmology, 20*(5), 231–239.
Levi, D. M., & Klein, S. A. (1990). Equivalent intrinsic blur in spatial vision. *Vision Research, 30*(12), 1971–1993.
Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*(2), 467 (Suppl. 2).
Majaj, N. J., Pelli, D. G., Kurshan, P., & Palomares, M. (2002). The role of spatial frequency channels in letter identification. *Vision Research, 42*(9), 1165–1184.
McAnany, J. J., & Alexander, K. R. (2008). Spatial frequencies used in Landolt C orientation judgments: Relation to inferred magnocellular and parvocellular pathways. *Vision Research, 48*(26), 2615–2624. http://dx.doi.org/10.1016/j.visres.2008.02.012.
McAnany, J. J., Alexander, K. R., Lim, J. I., & Shahidi, M. (2011). Object frequency characteristics of visual acuity. *Investigative Ophthalmology & Visual Science, 52*(13), 9534–9538. http://dx.doi.org/10.1167/iovs.11-8426.
NAS-NRC (1980). Recommended standard procedures for the clinical measurement and specification of visual acuity. Report of working group 39. Committee on vision. Assembly of Behavioral and Social Sciences, National Research Council, National Academy of Sciences, Washington, DC. *Advances in Ophthalmology, 41*, 103–148.
Ng, J., & Westheimer, G. (2002). Time course of masking in spatial resolution tasks. *Optometry and Vision Science, 79*(2), 98–102.
Niwa, K., & Tokoro, T. (1997). Measurement of temporal summation of visual acuity with use of modified tachistoscope. *Japanese Journal of Ophthalmology, 41*(6), 403–408.
Peli, E. (1990). Contrast in complex images. *Journal of the Optical Society of America A: Optics, Image Science, and Vision, 7*(10), 2032–2040.
Piéron, H. (1952). *The sensations: Their functions, processes, and mechanisms*. London: F. Müller.
Regan, D., Raymond, J., Ginsburg, A. P., & Murray, T. J. (1981). Contrast sensitivity, visual acuity and the discrimination of Snellen letters in multiple sclerosis. *Brain, 104*(2), 333–350.