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

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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,

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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 $\times$ 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