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Resolution of static and dynamic stimuli in the peripheral visual field

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ABSTRACT

In a clinical setting, emphasis is given to foveal visual function, and tests generally only utilize static stimuli. In this study, we measured static (SVA) and dynamic visual acuity (DVA) in the central and peripheral visual field on healthy, young emmetropic subjects using stationary and drifting Gabor patches. There were no differences between SVA and DVA in the peripheral visual field; however, SVA was superior to DVA in the fovea for both velocities tested. In addition, there was a clear naso-temporal asymmetry for both SVA and DVA for isoeccentric locations in the visual field beyond 10° eccentricity. The lack of difference in visual acuity between static and dynamic stimuli found in this study may reflect the use of drift-motion as opposed to displacement motion used in previous studies.

1. Introduction

The visual world in which we live contains both static and dynamic components. As such, the visual system has developed to respond to a wide variety of stimuli.

The most widely used measure of visual function is the measurement of visual acuity, which is the ability of the eye to resolve detail in an image. The conventional method of measuring visual acuity employs stationary letters or symbols (optotypes) of high contrast viewed at a specific testing distance. In a clinical setting emphasis is concentrated on foveal visual acuity; in fact, it is generally only foveal acuity that is measured for example when assessing suitability for holding a motor vehicle driving license in many countries (Bohensky, Charlton, Odell, & Keeffe, 2008).

Resolution thresholds of the eye are limited by the optics of the eye, the spacing of the photoreceptors and the spacing of ganglion cells in the retina (Anderson, Mullen, & Hess, 1991; Atchison, Schmid, & Pritchard, 2006; Banks, Sekuler, & Anderson, 1991; Campbell & Green, 1965; Ennis & Johnson, 2002; Frisén & Glansholm, 1975; Lundström et al., 2007; Millodot, Johnson, Lamont, & Leibowitz, 1975; Popovic & Sjöstrand, 2005; Thibos, Cheney, & Walsh, 1987; Wang, Thibos, & Bradley, 1997; Williams, Artal, Navarro, McMahon, & Brainard, 1996).

In the fovea, spatial resolution is predominantly optically limited, in contrast to the periphery (beyond 10°) where spacing of midget ganglion cells is the major factor determining the limits of resolution (Anderson, Wilkinson, & Thibos, 1992; Banks et al., 1991; Campbell & Green, 1965; Curcio & Allen, 1990; Frisén & Glansholm, 1975; Lundström et al., 2007; Millodot et al., 1975; Popovic & Sjöstrand, 2001, 2005; Thibos et al., 1987).

Static visual acuity (SVA) declines rapidly with increasing eccentricity from the fovea in a symmetrical fashion in both the nasal and temporal visual fields out to an eccentricity of approximately 10° (Anderson, Zlatkova, & Demirel, 2002; Frisén & Glansholm, 1975; Thibos et al., 1987). Beyond this, SVA is better in the temporal visual field than in the nasal visual field. These differences have been attributed to lateral asymmetry of retinal ganglion cells beyond the optic nerve head (Anderson et al., 2002; Fahle & Schmid, 1988; Frisén, 1987; Frisén & Glansholm, 1975; Rovamo, Virsu, Laurinen, & Hyvärinen, 1982).

When relative motion exists between an observer and an object of interest, there will also be a corresponding movement of the image of the object on the observer's retina in relation to the fovea. In order to maintain good image clarity, the eye must track and focus the moving object so that the image is correctly imaged upon the fovea. This requires a pursuit tracking movement of the eye. The term "dynamic visual acuity" (DVA) was first proposed by Ludvigh and Miller (1958) to describe the ability of the eye to resolve stimuli, moving in relation to an observer.

It is accepted that foveal DVA diminishes as the angular velocity of a stimulus increases (Bex, Dakin, & Simmers, 2003; Brown, 1972a, 1972b; Burg, 1965; Chung & Bedell, 2003; Demer, 1995; Demer & Amjadi, 1993; Fergenson & Suzansky, 1973; Ludvigh & Miller, 1958; Murphy, 1978; Westheimer & McKee, 1975). In addition to velocity dependence, other factors affecting DVA have also been widely studied. These include illumination, pupil diameter, contrast, gender, age, alcohol, marijuana, and training effects. Further information regarding these factors can be found in the review articles by Miller and Ludvigh (1962) and Morrison (1980), as well as in Dwight Holland's (2001) doctorial thesis.

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Most studies of DVA have examined stimuli moving at relatively large angular velocities and those utilizing eye-tracking devices show that inadequate pursuit eye-movements is the key factor resulting in decreased DVA (Barmack, 1970; Brown, 1972a; Demer & Amjadi, 1993; Reading, 1972a). This "mismatch" between eye-movements and stimulus velocity causes retinal image slip, which results in movement of the image relative to the fovea.

The majority of researchers have used Landolt C stimuli (Emoto, 2010; Haarmeier & Thier, 1999; Long & Johnson, 1996; Ludvigh & Miller, 1958; Miller, 1958; Miller & Ludvigh, 1962; Peters & Bloomberg, 2005; Reading, 1972b; Smither & Kennedy, 2010; Ueda, Nawa, Yukawa, Taketani, & Hara, 2006) although there are a few exceptions. Behar, Kimball, and Anderson (1976) and Burg (Burg, 1966; Burg & Hulbert, 1961) used Bausch & Lomb checkerboard targets. Demer and Amjadi (1993) used Sloan optotypes. Geer and Robertson (1993) and Schneiders et al. (2010) both utilized Landolt E stimuli. Gratings in various forms have been used by McKee and Nakayama (1984) and Aznar-Casanova, Quevedo, and Sinnett (2005).

Differences in DVA between different stimuli have been reported, whereby the major factor affecting performance is the orientation of stimulus in relation to the direction of movement (Prestrude, 1987).

The type of stimulus also dictates the type of movement that can be presented; displacement motion or drifting motion. During displacement motion, the stimulus changes position in the visual field over time. For drifting motion the stimulus remains at the same location whilst every element of the pattern undergoes a temporal phase change; giving the impression of movement within an aperture (Aznar-Casanova et al., 2005). Gratings and Gabor patches can be utilized to show both displacement and drift motion, whereas other stimuli can only be presented using displacement movement.

The disadvantage of displacement motion is that stimuli do not remain at the same location and consequently, the retinal area stimulated varies depending on both stimulus velocity and duration.

It is important to note that subjects in the majority of previous studies had to follow moving stimuli, and that the associated reduction in DVA occurred when ocular pursuit movements were no longer able to maintain the stimulus on the fovea.

Two noteworthy studies conducted Brown (1972a, 1972b) examined DVA in the peripheral visual field in the absence of voluntary eye-movements. DVA using displacement motion and under steady fixation, deteriorated when relative movement exceeded approximately 2–4°/s. These results have also been repeated by Demer and Amjadi (1993) and Aznar-Casanova et al. (2005). Aznar-Casanova et al. (2005) used an exposure duration of 700 ms, whereas Demer and Amjadi (1993) used 16 s, and Brown (1972a, 1972b), 400 ms.

In the case of drifting motion, deterioration in DVA begins from velocities as low as 0.5°/s (Aznar-Casanova et al., 2005) showing that the mechanisms behind impaired performance are not identical for displacement and drifting motion.

The aim of this study was to measure SVA and DVA at specific locations in the horizontal visual field on healthy, young emmetropic subjects. The stimuli, namely stationary and drifting Gabor patches, were chosen as these allowed well-defined retinal locations to be tested irrespective of stimulus velocity.

2. Methods

2.1. Apparatus

Stimuli were generated on a PC microcomputer (MSI K9A2 Platinum motherboard) running Windows XP and MATLAB® software (MathWorks, Natick, MA) with extensions supplied with the Psychophysics Toolbox (Brainard, 1997). Four ATI Radeon™ HD 4350 graphic cards were used to drive 8 IBM (G96) 19″ CRT monitors with a resolution of 1280 × 1024 (dot pitch 0.25 mm) with a refresh rate of 85 Hz and with a mean luminance of 43–45.3 cd/m^2. An **i1**Display 2 colorimeter from X-Rite was used to calibrate and correct the luminance and gamma function of the monitors. One of the eight monitors was used solely as a slave monitor to control stimulus presentation within Matlab on the remaining monitors.

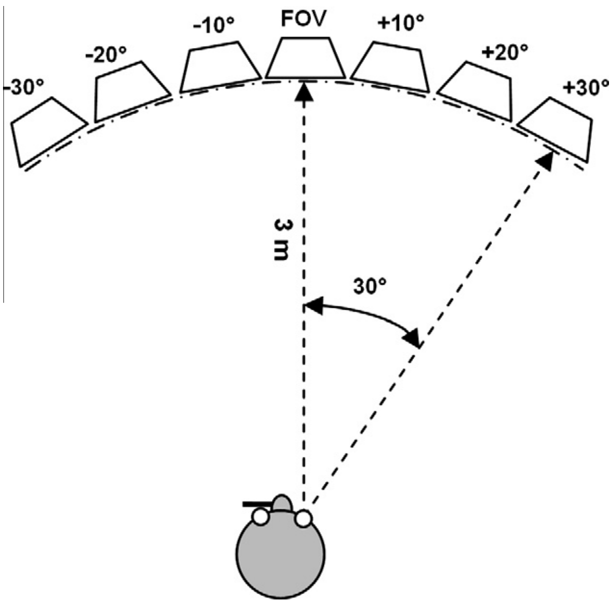

Fig. 1. Experimental setup with seven CRT-screens. The subjects fixated on the central screen (FOV) with their right eye, whilst the left eye was occluded with a patch. Negative eccentricity (−10° to −30°) represents the nasal visual field of the right eye, whereas positive eccentricity (+10° to +30°) represents the temporal visual field.

The remaining seven monitors were situated at a distance of 3.0 m from the subject thus forming an arc with a constant radius of 3.0 m (see Fig. 1). A forehead-rest was utilized to maintain this observation distance without restricting the horizontal visual field.

2.2. Stimulus generation

Test stimuli consisted of circular Gabor patches (i.e., $\sigma_x = \sigma_y$) with a visible angular diameter of 2° (σ = 0.5°). Only high contrast (98% or greater) stimuli were used in this study.

The general formula for the Gabor stimuli was as follows:

$$L(x,y) = L_m[1 + \sin(2\pi x f_s + \phi)] \times \exp[-(x^2 + y^2)/(2\sigma^2)]$$

Dynamic stimuli were identical to static stimuli in every respect except that the sine wave function was temporally modulated, creating an associated translation of the grating within the Gaussian envelope. Two velocities were adopted: 1°/s and 2°/s and the direction of movement were always laterally, from right to left (creating similar motion as if reading a text from left to right). The choice of tested velocities was based upon previous studies (Demer, 1995; Demer & Amjadi, 1993; Westheimer & McKee, 1975) showing marked deterioration of visual acuity for stimuli drifting at velocities greater than approximately 2°/s.

The Gabor patches were orientated obliquely; leaning either ±45° from the vertical in order to reduce the superiority of acuity for gratings orientated vertically or horizontally (Berkley, Kitterle, & Watkins, 1975; Campbell, Kulikowski, & Levinson, 1966; Westheimer, 2003) and the possible influence of off-axis astigmatism in the peripheral visual field (Gustafsson, Terenius, Buchheister, & Unsbo, 2001; Rempt, Hoogerheide, & Hoogenboom, 1976).

2.3. Experimental method

Resolution thresholds were determined for 0, 1 and 2°/s at the following retinal locations: in the fovea, 10°, 20° and 30°; both nasally [−] and temporally [+].

2.3.1. Subjects

A total of 10 naïve subjects participated (mean age 25.5 years, ranging from 19 to 38 years). All were emmetropic (refraction ⩽ ±0.50D and astigmatism < −0.50DC) and had unaided foveal visual acuities of 6/6 or better and no known ocular disease. Subjects viewed the fixation screen with their right eye while wearing a patch over their left eye. No optical correction was utilized foveally or eccentrically.

Written informed consent was obtained from each subject after the nature and purpose of the experiment had been explained. The tenets of the Declaration of Helsinki were followed.

2.3.2. Procedure

Subjects were seated at a distance of 3.0 m from the seven monitors and instructed to observe a fixation target (in the form of a magnified asterisk "∗") on the centermost monitor for all measurements except for those in the fovea where the fixation target was replaced by the stimulus.

Each measurement trial was initiated by the subject pressing a key on a modified numerical keypad. A tone preceded each stimulus presentation. Following a delay of 500 ms, the stimulus appeared on the monitor being tested and remained visible for a duration of 300 ms; this to avoid saccadic re-fixation eye-movements. All responses were recorded using the modified numerical keypad.

The thresholds were determined by a two-alternative forced-choice (2AFC) procedure in which the subjects had to determine the orientation of the grating. The threshold value corresponded to the stimulus strength estimated giving 75% correct response rate and the psychometric function was assumed to be logistic. An adaptive Bayesian algorithm proposed by Kontsevich and Tyler (1999) was used to calculate a probability density function for the threshold, with the expectation value taken as the measurement. After 31 trials the probability density function in general assumed a normal distribution, with an average standard deviation of 0.085 log MAR.

Resolution thresholds were obtained at one retinal eccentricity at a time so that visual attention was concentrated on the correct location. The order of testing followed a predetermined random protocol in order to reduce possible training effects and subjects were given the opportunity to take breaks between trials.

2.3.3. Control experiments

Two control experiments were performed in order to determine the effect of exposure duration and to ascertain the highest spatial frequency at which the subject could still perceive motion of Gabor stimuli moving at 1 and 2°/s.

In the first control experiment, which in effect followed the same procedure as in the main experiment, resolution thresholds were measured using exposure durations of 300, 700 and 1500 ms at 10° and 20° in the nasal visual field of three subjects who had participated in the previous experiment. The average of three measurements was recorded for each eccentricity and velocity.

In the second control experiment, exposure duration was maintained at 300 ms whilst spatial frequency was altered, however the aim of this experiment was to see the highest spatial frequency whereby the subject could still perceive movement of the Gabor patch. The same two velocities were used as in the main experiment, namely 1 and 2°/s. One experienced subject (PL) participated in this experiment. The average of three series consisting of 45 trials was recorded for both velocities and for eccentricities of 10° and 20° in the nasal visual field.

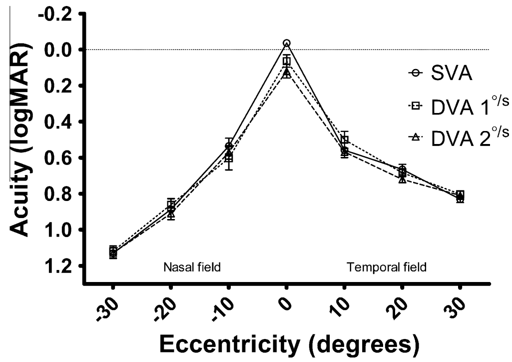

Fig. 2. Mean static and dynamic acuity for all subjects. Error bars denote ± SEM.

3. Results

The main result of this study is that there were no differences between SVA, $DVA^{1°/s}$ and $DVA^{2°/s}$ in the periphery for the mean of the population tested. This was confirmed by two-way repeated measures ANOVA ($p > 0.05/3$) with adjustment for multiple comparisons (Bonferroni) at all eccentricities. The exception was the fovea, where SVA was better than both $DVA^{1°/s}$ ($p < 0.05$) and $DVA^{2°/s}$ ($p < 0.01$). There was however no difference between $DVA^{1°/s}$ and $DVA^{2°/s}$ in the fovea.

The mean visual acuity ± one standard error of the mean (SEM) for all subjects under static and dynamic conditions is shown in Fig. 2.

One-way repeated-measures ANOVA followed by Bonferroni multiple comparisons showed significantly differences between the nasal and temporal visual fields for eccentricities of 20° and 30° for SVA, $DVA^{1°/s}$ and $DVA^{2°/s}$. There was however no naso-temporal asymmetry between SVA, $DVA^{1°/s}$ and $DVA^{2°/s}$ at an eccentricity of 10°.

The mean of all values for SVA and DVA for all subjects are presented below in Table 1.

3.1. Results of control experiments

Results of the first control experiment (see Fig. 3), in which exposure duration was altered, showed no significant difference in visual acuity between 300, 700 and 1500 ms for stimuli moving at a velocity of 1°/s at two tested locations in the nasal visual field.

Thresholds for perceiving movement of 1 and 2°/s were obtained on one subject (see Fig. 4). The highest spatial frequency in which movement was still perceived at 1°/s was 0.57 log MAR at 10 N and 0.60 log MAR at 20 N. For a velocity of 2°/s the threshold were 0.93 log MAR and 0.77 log MAR respectively for 10° and 20° in the nasal visual field. This means the subject was able to discern that stimuli were in motion up to, or even above the limit of resolution for an exposure duration of 300 ms.

4. Discussion

This study on a population of healthy young emmetropes showed no difference between static (SVA) and dynamic visual acuity (DVA) at eccentricities of ±10°, 20° and 30°. Foveal

Table 1
Mean static and dynamic log MAR acuities (±1SEM) for all subjects.

	(Nasal)			Eccentricity	(Temporal)		
	−30	−20	−10	FOV	+10	+20	+30
SVA	1.13 ± 0.03	0.89 ± 0.06	0.53 ± 0.04	−0.04 ± 0.01	0.56 ± 0.04	0.66 ± 0.03	0.83 ± 0.02
DVA$^{1°/s}$	1.12 ± 0.03	0.86 ± 0.03	0.60 ± 0.02	0.06 ± 0.03	0.50 ± 0.05	0.68 ± 0.02	0.80 ± 0.02
DVA$^{2°/s}$	1.13 ± 0.03	0.91 ± 0.03	0.50 ± 0.02	0.12 ± 0.04	0.57 ± 0.02	0.72 ± 0.02	0.81 ± 0.02

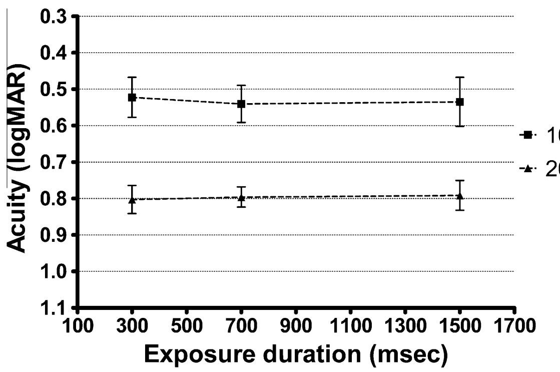

Fig. 3. The effect of exposure duration on visual acuity at 10° (squares "■") and 20° (triangles "▲") in the nasal visual field. Error bars represent the standard error of the mean (SEM) of three repeated measurements on three subjects.

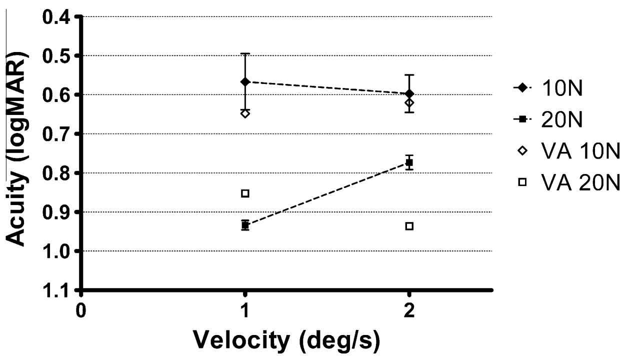

Fig. 4. Motion discrimination thresholds as a function of velocity at 10° and 20° in the nasal visual field on one experienced subject (PL). Filled diamonds "♦" and squares "■" represent the average of three measurements at 10° and 20° respectively in the nasal visual field (error bars represent the standard deviation of these three measurements). Open symbols represent previously measured visual acuity at the same locations and velocities.

resolution was best for SVA and decreased with increasing stimulus velocity. This is in accordance with previous studies that have measured DVA under conditions of steady fixation (Aznar-Casanova et al., 2005; Brown, 1972b; Demer & Amjadi, 1993; Macedo, Crossland, & Rubin, 2008; Nes, 1968). Aznar-Casanova et al. (2005) showed that visual acuity measured using drifting gratings decreased with increasing stimulus velocity. They found that in the case of drift motion, foveal visual acuity began to deteriorate from as little as 0.5°/s, which supports the findings in this study. The visual system on the other hand has been shown to tolerate retinal motion of 2–4°/s when viewing stimuli moving within the visual field, also termed "displacement motion" (Demer & Amjadi, 1993).

In contrast to earlier studies of DVA in which displacement motion was employed (Brown, 1972a, 1972b; Burg, 1965; Geer & Robertson, 1993; Ludvigh & Miller, 1958; Macedo, Crossland, & Rubin, 2011; Miller, 1958; Peters & Bloomberg, 2005; Reading, 1972b; Ueda et al., 2006) we have endeavored to measure visual acuity at specific locations in the visual field by using a drifting Gabor-patch of a fixed angular size. The area stimulated in this study was limited to 2° irrespective of stimulus velocity, whereas for example, in Brown's study (1972a) the stimuli traversed a greater area of the retina as stimulus velocity increased. This is one possible explanation for the perceived improvement in peripheral visual acuity for relatively low stimulus velocities (under 10°/s) found in their studies; namely, that the retinal area tested enlarged as stimulus velocity increased.

Similar results have been obtained by Macedo et al. (2008) for non-crowded stimuli whereby visual acuity improved slightly with increased retinal slip. In contrast, peripheral visual acuity deteriorated substantially for crowded stimuli. Above a certain threshold, a corresponding retinal image slip results in a deterioration in acuity. Demer and Amjadi (1993) reported that foveal visual acuity deteriorated rapidly for retinal image motion in the order of 2–4°/s (measured by displacement motion). Aznar-Casanova et al. (2005) also determined that for low velocity stimuli (0–5°/s) visual acuity deteriorated at least two and a half times faster for displacement motion than for drifting motion, as used in this study.

The results of this study confirm previous studies, which evaluated various measures of peripheral visual function (resolution, detection, contrast thresholds, temporal resolution, etc) in that a clear naso-temporal asymmetry for SVA exists. SVA is better in the temporal visual field than in the nasal visual field, as can be seen in Fig. 2. Curcio and Allen (1990) showed that the basis of this naso-temporal asymmetry is anatomical; cell counts show higher density in the nasal retina than in the temporal retina. Ganglion cell receptor fields also show same asymmetry.

The observed reduction in acuity may, in part, also reflect the naso-temporal asymmetry of optical aberrations in the periphery, whereby both lower-order and higher-order aberrations are more pronounced in the nasal visual field (Atchison, Pritchard, White, & Griffiths, 2005; Gustafsson et al., 2001).

However other research (Rosén, Lundström, & Unsbo, 2011) show no difference in resolution thresholds for high-contrast static and dynamic stimuli after correction of optical defocus. It would be interesting to study the effect of correction on low-contrast DVA in the future.

To our knowledge, no studies have evaluated DVA at multiple retinal locations along the horizontal visual field. This study shows a clear naso-temporal asymmetry for both SVA and DVA based on the averaged results of 10 subjects.

The average difference in SVA and DVA between the nasal and temporal visual fields at 30° was approximately 0.3 log MAR, and at 20°, approximately 0.2 log MAR. There was no apparent difference at 10° other than for a stimulus velocity of 1°/s whereby the average threshold was 0.1 log MAR lower in the temporal visual field than in the nasal visual field.

5. Conclusions

This study on a population of young emmetropes showed, for isoeccentric locations in the visual field beyond 10° eccentricity, a clear naso-temporal asymmetry for both SVA and DVA, measured using high-contrast stimuli. There were no differences between SVA and DVA in the peripheral visual field, however foveal SVA was superior to DVA for both velocities tested.

The lack of difference in visual acuity between static and dynamic stimuli found in this study may reflect the use of drift-motion as opposed to displacement motion used in previous studies. The specific area tested also remained constant irrespective of stimulus velocity.

These findings are possibly more pertinent for patients with central visual field loss (CFL) in that, such patients are restricted to using a limited peripheral retinal location when observing both static and dynamic stimuli.

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