View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com

SCIENCE DIRECT

Vision Research 46 (2006) 2487–2498

Vision Research

www.elsevier.com/locate/visres

Binocular interactions in patients with age-related macular degeneration: Acuity summation and rivalry

Luminita Tarita-Nistor [a,b], Esther G. González [a,b,c], Samuel N. Markowitz [b,c], Martin J. Steinbach [a,b,c,*]

[a] *Centre for Vision Research, York University, Toronto, Canada*
[b] *Vision Science Research Program, Toronto Western Hospital, Toronto, Canada*
[c] *Department of Ophthalmology, University of Toronto, Canada*

Received 15 August 2005; received in revised form 19 January 2006

Abstract

This study examined two aspects of binocular function in patients with age-related macular degeneration (AMD): summation/inhibition of visual acuity and rivalry. The performance of 17 patients with AMD was compared with that of 17 elderly controls and 21 young people. Monocular and binocular acuities were measured using a multiple-E optotype test. Binocular ratios, defined as the better-eye acuity divided by the binocular acuity, were calculated. We also measured eye dominance during rivalry (proportion of time the participants reported perceiving the input to each eye) and rivalry rates (number of alternations per minute). The results showed that while overall binocular ratios were similar for the three groups, the frequency distributions of people who experienced inhibition, equality or summation were different for the young and AMD groups. In the rivalry test, patients experienced more piecemeal perception than the elderly and young controls, but time dominance from the better-seeing eye was comparable for the three groups. Rivalry rates decreased with age and further with pathology. Moreover, rivalry time dominance of the worse-seeing eye was negatively correlated with interocular acuity differences for the AMD group.
© 2006 Elsevier Ltd. All rights reserved.

Keywords: Age-related macular degeneration; Acuity; Rivalry; Binocular interactions

1. Introduction

In developed countries, age-related macular degeneration (AMD) is the leading cause of legal blindness in people 65 years or older, and recognized as a disabling factor in an ageing population. It is estimated that the incidence of the disease will increase sharply because of the ageing of the baby boomers (Eye Disease Prevalence Research Group, 2004). AMD destroys the macula, the part of the retina with the highest concentration of photoreceptors, resulting in the loss of central vision (Edwards, Bressler, & Raja, 1999). Typically, deterioration of the macula causes the development of scotomas or blind spots, and blurred or distorted central vision. Although AMD affects central vision, peripheral vision may remain unaffected.

There are many implications of central vision loss. For example, depending on the stage of the disease, patients with AMD have difficulties recognizing familiar faces and facial expressions (Bullimore, Bailey, & Wacker, 1991; Tejeria, Harper, Artes, & Dickinson, 2002), have a reduced reading acuity and reading speed (Ergun et al., 2003), and decreased mobility performance under certain conditions (Elliott et al., 1995; Hassan, Lovie-Kitchin, & Woods, 2002). These impairments have a devastating impact on the patients' ability to perform activities of daily living independently, and on their perceived quality of life. Given the prevalence and implications of AMD, it is important to understand how this disease affects other visual functions such as binocular acuity summation and rivalry.

* Corresponding author.
E-mail address: mjs@yorku.ca (M.J. Steinbach).

0042-6989/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2006.01.035

1.1. Binocular summation

Normally sighted observers typically perform visual tasks better with two eyes than with one eye. This is known as binocular summation and is defined as an increase in binocular performance compared with either of the two monocular performances when the sensitivities of the two eyes are equal (Blake & Fox, 1973). Binocular summation is usually explained with probability and neural summation models. The maximum binocular superiority explained on probabilistic grounds is offered by Pirenne's classical probability summation model, which predicts a 50% binocular improvement, providing that the two monocular performances are equal (Howard, 2002). Other probability models, adjusted for noise and guessing factors, predict a smaller binocular superiority (Blake & Fox, 1973). Binocular improvement exceeding the values predicted by probability models is usually explained with neural summation models; they extend the prediction of the binocular gain to more than double the monocular performance. Binocular superiority is often quantified as binocular ratio (BR) (Gagnon & Kline, 2003; Pardhan, 1996, 1997; Pardhan & Whitaker, 2000). When measuring acuity, BR is defined as best monocular acuity divided by binocular acuity.

In general, studies of contrast summation using light or sine-wave grating detection tasks with foveal stimulation show that normally sighted observers have a $\sqrt{2}$ binocular improvement (Legge, 1984; Pardhan, 1996), but it has been found that binocular contrast summation is affected by factors such as age, spatial frequency, stimulation of different retinal points, and unequal monocular contrast sensitivities. Studies of normally sighted people show that binocular and monocular contrast sensitivities decrease with age, but conflicting results about the role of age on binocular ratio have been obtained (Gagnon & Kline, 2003; Pardhan, 1996; Ross, Clarke, & Bron, 1985). Moreover, binocular contrast summation of young observers is the same whether using peripheral or foveal vision (Pardhan & Whitaker, 2003), and decreases when unequal monocular contrast levels are induced (Pardhan, Gilchrist, Douthwaite, & Yap, 1990).

Higher order processing tasks, such as recognition tasks, yield a lower binocular gain (expressed as BR) than detection tasks (Frisen & Lindblom, 1988). For example, it has been found that binocular acuity measured with acuity charts is 9–11% greater than monocular performance at high contrast (Frisen & Lindblom, 1988; Heravian, Jenkins, & Douthwaite, 1990; Home, 1978; Horowitz, 1949). Older people with minimal interocular acuity differences show an even smaller binocular acuity gain when their performance is measured with the ETDRS acuity charts (Rubin, Muñoz, Bandeen-Roche, & West, 2000). Binocular and monocular visual acuities increase with increasing contrast, but binocular acuity gain is small and independent of contrast (Cagenello, Arditi, & Halpern, 1992). In addition, binocular acuity ratios do not differ with age for normally sighted observers (Gagnon & Kline, 2003), and a high proportion of observers do not show binocular acuity superiority (Azen et al., 2002).

In people with AMD one eye is usually less affected than the other. As a result, the visual inputs from the two eyes differ considerably, and in some people binocular summation may be affected in such a way that binocular performance is worse than that of the best eye alone. This phenomenon is known as binocular inhibition. In fact, some patients acknowledge that they close the bad eye when they want to see fine details (Quillen, 2001). Recently, the question of whether people with AMD see better with only their better eye than with both eyes has been raised empirically in studies of contrast sensitivity. Faubert and Overbury (2000) and Valberg and Fosse (2002) found binocular contrast inhibition in a large proportion of patients with AMD, but just for gratings of low and medium spatial frequencies. The control groups were not ideal in both studies (considerably smaller in size or much younger), but despite these limitations, both studies showed that a high number of patients with AMD experience inhibition in detection tasks. These findings lead to a question worth exploring—whether this disease also affects binocular acuity summation in recognition tasks.

1.2. Rivalry

Binocular rivalry occurs when two very dissimilar images are separately presented to the two eyes and compete for perceptual awareness, resulting in the dominance of one image, which is later suppressed by the other image. These changes in the image dominance are irregular over time and unfold in "a wave-like manner over space" (Blake & Logothetis, 2002, p. 1). When stimuli are small, they produce exclusive dominance, in which all of one stimulus or all of the other is seen in alternation. When the stimuli are large, they may also produce mosaic or piecemeal dominance, which is characterised by a part of one stimulus being dominant in one area and a part of the other stimulus being dominant in another area (Howard, 2002). Often, the stimuli used in the study of rivalry are orthogonal gratings presented dichoptically at different levels of contrast and spatial frequencies. Sine-wave gratings of low spatial frequency (0.5 cpd) rival immediately after stimuli presentation, even at threshold contrast (Liu, Tyler, & Schor, 1992).

Generally, two key aspects of the rivalry processes have been studied: time dominance and alternation rate (rivalry rate). Time dominance is "the total viewing time in which the right and the left stimuli are visible" (Levelt, 1966, p. 226). Rivalry rate is the number of stimulus alternations in a given time. These two aspects are influenced by various factors such as the stimulus contrast, differences in the contrast levels of the two stimuli, size and eccentricity of the stimuli, amount of contour per area, spatial frequencies, observer's age, and ocular diseases (Blake, O'Shea, & Mueller, 1992; de Belsunce & Sireteanu, 1991; Levelt, 1966; Ukai, Ando, & Kuze, 2003).

Blake et al. (1992) showed that the rivalry rate decreases not only with increasing stimulus size, but also with increasing retinal eccentricity. Moreover, the rivalry rate of normally sighted observers also decreases with age. Ukai et al. (2003) compared the rivalry rates of young (20–34 years), middle-aged (35–49 years), and older (50–64 years) observers using small sized (1.8°) orthogonal stimuli. They recorded the time a vertical central line and the time a horizontal central line were uninterruptedly perceived, and then calculated the mean alternation times for the three groups. They found that rivalry rates decline as the age of the observers increases. Their study does not provide information about how sharp this decline is in people older than 65 years, who are most prone to AMD. In addition, the effect of age on rivalry rates when using orthogonal stimuli of a larger size has not been analysed.

The goal of the present study was to investigate binocular acuity summation (Experiment 1) and rivalry patterns (Experiment 2) in people with AMD.

2. Experiment 1: Acuity

Standard acuity charts used in clinical practice are designed to measure central, foveal acuities. With the ETDRS or Snellen charts, defective gaze selection and/or control can significantly reduce the measured acuity of patients with amblyopia or AMD. Harris, Robins, Dieter, Fine, and Guyton (1985) developed a multiple tumbing E optotype test to measure the best eccentric visual acuity of patients with AMD. Their test increases the chance that a letter will fall on a healthy part of the eccentric retina of a person with a damaged fovea and fixation instability. It consists of a series of ten multiple tumbling E optotype cards; the Es on a card are identical, but their size and orientation differ between cards. The patients' task is to identify the orientation of the optotypes on the cards. The letters measure from 20/20 to 20/200 equivalent Snellen acuity. Harris et al. found that the acuity of patients with AMD measured with this test is at least two times better than that measured by conventional methods, and therefore more appropriate for measuring the acuity of people with central vision loss. No study, to our knowledge, has used the test to evaluate the binocular acuity gain for patients with AMD, nor are we aware of studies that employ conventional methods for the same purpose. We asked the empirical question whether binocular ratio, as measured with the tumbling E test, is diminished in AMD patients indicating that they experience inhibition.

The primary purpose of Experiment 1 was to investigate whether AMD affects binocular acuity summation at different levels of contrast, by comparing the patients' acuity performance with that of a young and an elderly control group. Based on the characteristics of the disease (i.e., the loss of central vision, the two eyes are not affected equally) as well as on past research (Faubert & Overbury, 2000; Valberg & Fosse, 2002), we predicted the AMD group should show more binocular inhibition ($BR < 1$) than the elderly and young control groups.

2.1. Method

2.1.1. Participants

Seventeen patients with AMD (mean age = 81.6 years, SD = 6.8), twenty-one young controls (mean age = 33.4 years, SD = 9.3), and seventeen elderly controls (mean age = 74.1 years, SD = 6.9) participated in the study. The latter group was intended to be an age-matched control for the AMD group, but an independent t test showed that the difference between age means was significant ($t(32) = -3.186$, $p < .01$). It was difficult to find older volunteers who had no ocular disease. The mean stereopsis measured with the Titmus test (Titmus Optical Co., Inc., Petersburg, Virginia 23805) was $M = 41.9$ s arc (SD = 4.02) for the young control group, and $M = 60$ s arc (SD = 34.64) for the elderly control group. The Titmus test could not detect any stereopsis for eight of the patients; the other nine had a mean stereopsis of $M = 672$ s arc (SD = 268.22). All participants wore their spectacle correction during testing, if needed.

Inclusion/exclusion criteria: The patients had a confirmed diagnosis of AMD from an ophthalmologist, and corrected visual acuity better than 20/200 in the better-seeing eye and not worse than 20/800 in the worse-seeing eye. Given that acuity decreases with age, the elderly control subjects had a corrected visual acuity of 20/40 or better in both eyes, while the young control participants had a visual acuity 20/20 or better in both eyes. The patients and elderly controls had no other significant ocular disease other than incipient cataract. Patients with a history of neurological disease or cognitive impairment were not included in this study. All patients and elderly control participants underwent an ophthalmological examination prior to testing.

Patients with AMD were recruited from referrals to the Low Vision Clinic at the Toronto Western Hospital and the elderly control participants from two private practice ophthalmological clinics. Young control participants were recruited from various sources, including hospital employees, university students, and patients' relatives. Informed consent was obtained from all participants. The research was approved by the University Health Network Research Ethics Board and by the York University Human Participants Review Committee, and conducted in accordance with the tenets of the Declaration of Helsinki.

2.1.2. Apparatuses and stimuli

Monocular and binocular acuities at three different contrasts were measured using a modified version of the multiple tumbling E acuity test (González, Markowitz, & Steinbach, 2004), based on the work of Harris et al. (1985). The stimuli were generated with VPixx (VPixx Technologies, Inc., Montreal, QC), a graphics generation and psychophysics testing software, controlled by a MacIntosh G4 computer and displayed on a Samsung monitor with a 36×27 cm^2 viewing area.

The Multiple E test consists of a full screen array of identical Snellen E letters, all oriented in the same

direction in one of the four cardinal orientations. The aspect ratio (width/height) of each letter is equal to 1 and they are all staggered along 45 deg diagonals. The spacing is proportional to the size of the letters. The program presented multiple light tumbling E optotypes on a dark background at three different Michelson contrast levels: 86%, 32%, and 12% (see Fig. 1). The letters' orientation (up, down, left, or right) changed randomly from one trial to another and thresholds were measured using a four-alternative forced-choice (4AFC) psychophysical staircase with a logarithmic scale and a step size of 0.1 log units. The size of the "E"s changed with the participant's responses using a one up/three down rule (Levitt, 1971). The program terminated the condition after eight reversals or sixty trials, and the acuity threshold was the average of the last four reversals. The trials were self paced and the participants viewed each array of Es for four seconds. Prior to testing, the experimenter described the stimuli and the task, and all participants knew that it was enough to identify one of the E's correctly.

2.1.3. Procedures

Left eye, right eye, and binocular acuities were measured with the multiple E test at the three levels of contrast, in random order. The patients with AMD were tested at 1 m and all control participants at 3 m, with the room illumination turned off.

2.1.4. Data analysis

Based on the monocular acuity values measured with the tumbling E test, better-seeing and worse-seeing eyes were established at the three levels of contrast for each participant. For the AMD group, the monocular acuity values for the better-seeing eye at the highest contrast correlated highly with those from the ETDRS from the clinical assessment, ($r(32) = .90$, $p < .001$). Binocular ratios (BR) were calculated for each participant as the ratio of better monocular to binocular acuity in minutes of arc.

The F approximations of Wilks' Lambda in multivariate analysis are reported here, but the same results and comparable power were found using univariate tests with the Geisser–Greenhouse conservative F statistic. Pairwise comparisons between groups were made using Tukey's HSD test and a critical probability value of 0.05 was used. For multiple comparisons, familywise error was controlled using Holm's sequential Bonferroni approach and the critical probability adjusted accordingly.

2.2. Results

2.2.1. Acuity

Acuity thresholds were analyzed with a 3 (Group) × 3 (Contrast) × 2 (Eye Condition) mixed factorial analysis of variance (MANOVA), with Group as the between-subjects variable (AMD, elderly controls, and young controls), and levels of contrast (86%, 32%, and 12%) and eye condition (best monocular vs. binocular) as within-subject variables (means and standard deviations are presented in Table 1). The Group and Contrast main effects, and Contrast × Group interaction were significant. Follow-up analysis done with six planned paired-samples t tests, controlled for familywise error rate, ($p < .005$) revealed a significantly better binocular acuity at high contrast than at medium contrast, and at medium contrast than at low contrast for all three groups. Best monocular and binocular acuity means and standard errors for the three groups at high (86%), medium (32%), and low (12%) contrast levels are plotted as a function of contrast and group in Fig. 2.

Three planned one-way ANOVAs ($p < .005$) assessed differences among binocular acuities of the three groups at each contrast level. For binocular acuity at high contrast, there was a significant difference between groups ($F(2, 52) = 27.65$, $p < .005$). Post hoc analysis showed a significant difference between the young control group and the AMD group. The same pattern of results was found, following significant one-way ANOVAs, for medium

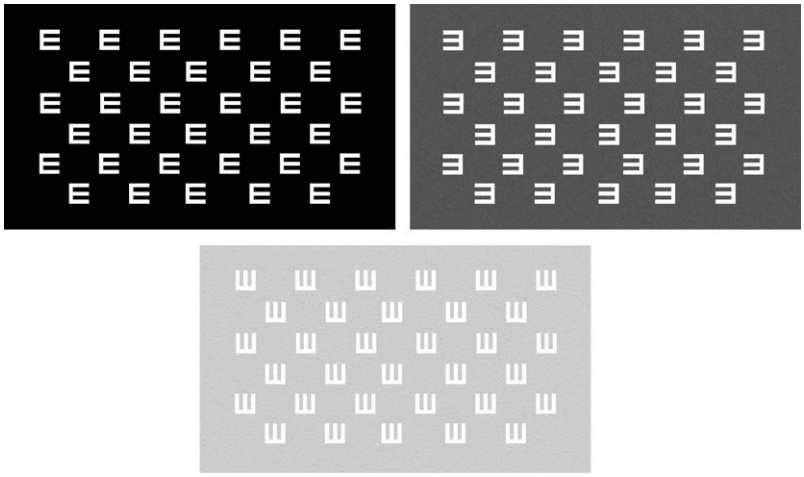

Fig. 1. Example of illiterate-E optotypes at three levels of contrast used in the acuity test.

Table 1
Mean (SD) acuity (arcmin) measured with the multiple E test

Group/eye condition	Contrast level		
	86%	32%	12%
Young control group			
Binocular acuity	.76 (.24)	1.06 (.17)	1.27 (.31)
Best monocular acuity	.81 (.22)	1.12 (.23)	1.37 (.40)
Elderly control group			
Binocular acuity	1.12 (.29)	1.61 (.52)	2.46 (.80)
Best monocular acuity	1.11 (.24)	1.66 (.48)	2.42 (.75)
AMD group			
Binocular acuity	5.03 (2.78)	6.61 (3.51)	9.18 (5.23)
Best monocular acuity	4.99 (2.70)	6.92 (3.64)	9.44 (5.72)

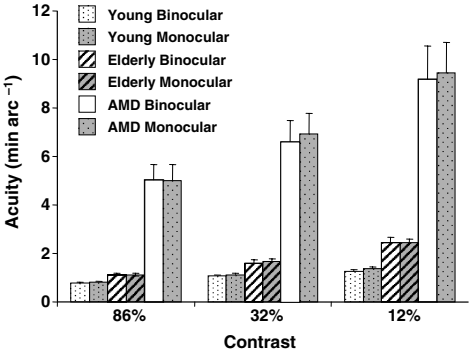

Fig. 2. Binocular and best monocular acuities for the AMD, young, and elderly control group. (±1 SE.)

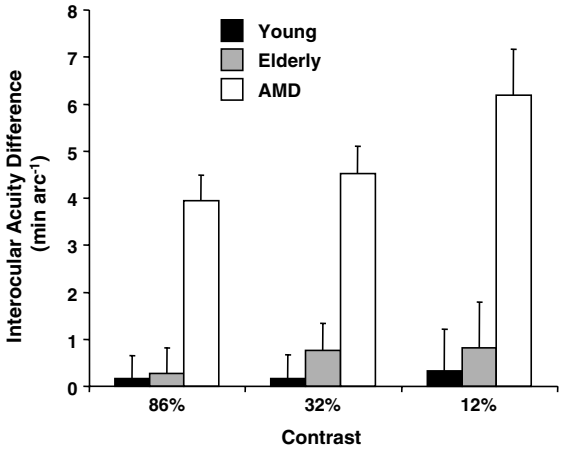

Fig. 3. Interocular acuity differences for the three groups.

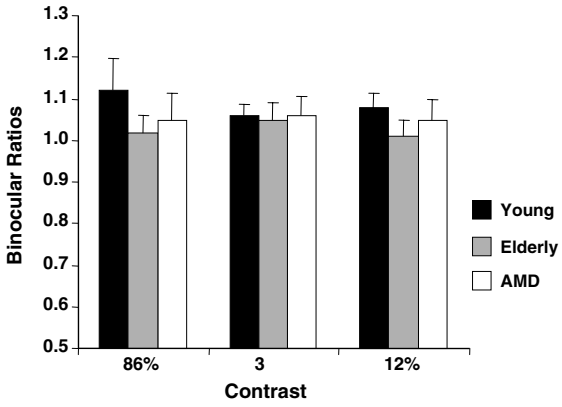

Fig. 4. Binocular ratio (BR) for the three groups at high, medium, and low contrast.

($F(2, 52) = 31.41$, $p < .005$) and low contrast ($F(2, 52) = 16.68$, $p < .005$).

2.2.2. Interocular acuity differences

For each participant, the acuity of the better-seeing eye was subtracted from that of the worse-seeing eye, and the differences among the means of the three groups assessed with a 3 (Group) × 3 (Contrast) repeated-measures analysis (MANOVA). There was a significant effect of Contrast ($F(2, 51) = 4.97$, $p < .05$) and Group ($F(2, 52) = 16.24$, $p < .05$), but no interaction effect. Pairwise comparisons (Bonferroni) revealed a significant difference between high and low contrast ($p < .05$), and Tukey HSD post hoc test, after a significant Group effect, showed that the AMD group had a higher mean interocular acuity difference that the two controls groups ($p < .05$). The means are displayed in Fig. 3.

2.2.3. Binocular ratio

Binocular ratio (BR) (better-seeing eye monocular acuity/binocular acuity) was analyzed with a 3 (Group) × 3 (Contrast) mixed factorial MANOVA. The multivariate tests showed that the main effects and interactions were all non significant. The means of the three groups at the three contrast levels are shown in Fig. 4.

The BR value was used as a categorization criterion in order to determine the frequency and amount of summation and inhibition for the three groups. Because we did not have a measure of test–retest reliability for our multiple optotype test, we used a range of 10% to define summation and inhibition values of BR. However, the discrepancy between binocular and monocular acuity were well within the limits of test–retest variability reported in the literature (Rosser, Cousens, Murdoch, Fitzke, & Laidlaw, 2003; Rubin et al., 2000). Summation was defined as a BR larger than 1.05, equality as a BR between .95 and 1.05 (1 ± .05), and inhibition as a BR < .95. Because contrast level did not affect BRs, the data were collapsed over the three levels of contrast. A two-way 3 × 3 contingency table analysis evaluated whether the number of patients with AMD who experienced inhibition, summation, or equality were the same as those of the young and elderly participants. Group (young control, elderly control, and AMD) and type of BR (summation, equality, or inhibition) were found to be significantly related (Pearson $\chi^2(4, N = 165) = 9.92$, $p = .04$, Cramer's $V = .17$). The percentage of participants in each group who experienced summation, equality, and inhibition are presented in Fig. 5. Of the three pairwise comparisons between groups, the only significant difference was between

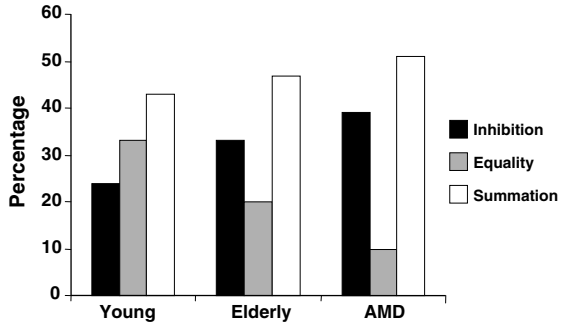

Fig. 5. Percentage of participants who experienced inhibition, equality, or summation for the three groups.

Table 2
Mean (SD) binocular ratios for the three groups

Group/condition	Contrast level			
	86%	32%	12%	Overall
Young control group				
Summation	1.37 (0.40)	1.19 (0.30)	1.23 (0.36)	1.27 (0.25)
Inhibition	0.86 (0.05)	0.86 (n/a)	0.90 (0.06)	0.87 (0.06)
Elderly control group				
Summation	1.20 (0.10)	1.15 (0.14)	1.12 (0.07)	1.16 (0.11)
Inhibition	0.86 (0.06)	0.87 (0.08)	0.82 (0.08)	0.87 (0.07)
AMD group				
Summation	1.25 (0.23)	1.21 (0.10)	1.21 (0.12)	1.22 (0.15)
Inhibition	0.82 (0.08)	0.87 (0.07)	0.87 (0.07)	0.85 (0.07)

the young controls and the AMD participants (Pearson $\chi^2(2, N=114)=9.42$, $p=.009$, Cramer's $V=.29$). The probability of a participant exhibiting inhibition was 1.65 times more likely when the participant was a patient with AMD than a young control. Conversely, young controls were 3.4 times more likely than participants with AMD to experience equality.

2.2.4. Summation and inhibition

Six planned one-way analysis of variance tests revealed no significant differences between the three groups in terms of inhibition or summation at any of the contrast levels, and no differences between contrast levels within each group, for summation or inhibition. Mean binocular ratios for participants who experienced summation or inhibition are presented in Table 2.

3. Experiment 2: Rivalry

The purpose of Experiment 2 was to investigate whether AMD affects binocular rivalry at different levels of contrast. Because there is no study, to our knowledge, dealing with rivalry in patients with AMD, this research examined how the disease affects the two key aspects of rivalry processes: time dominance and rivalry rate. The predictions were that: (1) rivalry dominance of the two eyes should be equal for the young and elderly control groups and that the better-seeing eye should be dominant for the patients with AMD; (2) rivalry rates should decrease as a function of contrast for all three groups; and, (3) rivalry rates should decrease with age and, because patients with AMD rely on the peripheral vision, their rivalry rate should decrease even further.

3.1. Method

3.1.1. Participants

The same participants as in Experiment 1, except one patient with AMD and two elderly controls, were tested. Acuity (Experiment 1) and rivalry were tested in a single session, with a short break between the tests. All participants completed the rivalry test at high, medium, and low contrast.

3.1.2. Apparatuses and stimuli

Horizontal and vertical sine wave gratings with a spatial frequency of 0.5 cpd were generated with VPixx (VPixx Technologies, Inc., Montreal, QC), using two MacIntosh computers. The stimuli were displayed dichoptically on two Samsung monitors with a 36×27 cm^2 viewing area. To ensure that the stimuli displayed by the monitors were equal, their parameters were tested on nine areas evenly distributed on the screens (corners, edges, and middle). The gratings were presented on the full screen at three contrast levels (86%, 32%, and 12%), and viewed through a mirror stereoscope at an optical distance of 48.6 cm. There were three blocks of trials, 60 s in duration. Rivalry dominance and rivalry rates were measured with a two-button response box, connected to a PC computer. The duration of each button press, as well as the rate of alternation were recorded using a program written in Visual Basic. A tactile clue, signaling which button corresponded to each grating, was given by a vertical or a horizontal stick glued on top.

3.1.3. Tests and procedures

Based on the monocular acuity thresholds measured in Experiment 1, the better-seeing and worse-seeing eyes were established for each participant, at the three levels of contrast. The orthogonal stimuli were presented dichopticaly on the two computer screens and viewed with the head steadied using the chin rest of the stereoscope. The observers' task was to hold the response box with both hands, and to press the corresponding button and keep it pressed as long as they saw the vertical or the horizontal gratings alone, or to press both buttons when the image was mixed. In order to avoid unwanted reflections from the screens, measurements were made with room illumination turned off.

3.1.4. Data analysis

Total time dominance of the better-seeing, worse-seeing eye, and both eyes (piecemeal perception) were recorded for each participant, at the three contrast levels. The total activity time was calculated by subtracting the

time when none of the buttons were pressed from the total trial time of 60 s. The results were reported as the percentage of time the better-seeing eye, the worse-seeing eye, and both eyes dominated during the total activity time of each trial.

The computer program of the button response box also recorded the number of times the image dominance changed during a trial. This number represented the rivalry rate per minute.

3.2. Results

3.2.1. Rivalry dominance

Time dominance from the rivalry test was assessed with a mixed-factorial MANOVA. Group (young control, elderly control, and AMD) was the between-subjects variable and Eye (better-seeing, worse-seeing, and both eyes) and Contrast (high, medium, and low) the within subject variables. There were significant effects of Group, Eye, and the Eye × Group interaction ($F(4, 100) = 4.20$, $p < .005$). Since contrast had no effect on time dominance, and in order to simplify the follow-up analysis, the data were collapsed over the three contrast levels. Once more, the effects of Eye, Group, and their interaction ($F(4, 318) = 9.01$, $p < .005$) were significant. The means and standard deviations are presented in Table 3.

The follow-up analysis of the Eye × Group interaction was done with six planned paired-sample t tests. Time dominance of the better-seeing eye was significantly higher than that of the worse-seeing eye for the AMD group, but not different for young and elderly control groups ($p < .05$). Conversely, time dominance of the worse-seeing eye was significantly higher ($p < .05$) than that of the both eyes (piecemeal perception) for the young and elderly control groups, but not for the AMD group.

In addition, three planned one-way ANOVAs were conducted to assess differences among time dominance of the three groups for the better-seeing eye, worse-seeing eye, and both eyes, controlling for familywise error rate. Time dominance for the better-seeing eye as the dependent variable and Group as the between-subjects variable showed a non significant effect. The same analysis for the worse-seeing eye, however, showed a significant difference between groups ($F(2, 159) = 15.35$, $p < .005$). Post hoc tests showed that the time dominance of the worse-seeing eye for the AMD group was significantly lower than those of the young and elderly control groups ($p < .05$), whereas the latter two groups did not differ. Likewise, a one-way ANOVA for piecemeal dominance showed a significant Group effect ($F(2, 159) = 15.35$, $p < .005$). This time, piecemeal dominance was significantly higher for the AMD group than for the other two groups ($p < .05$). The data are plotted in Fig. 6 as a function of Eye.

Table 3
Mean (SD) eye dominance in the rivalry test

Group/eye condition	Contrast level		
	86%	32%	12%
Young control group			
Better-seeing eye	38.46 (11.75)	40.60 (9.20)	39.47 (12.45)
Worse-seeing eye	39.55 (10.55)	40.98 (10.17)	40.93 (9.31)
Both eyes	21.99 (18.42)	18.42 (14.69)	19.60 (16.88)
Elderly control group			
Better-seeing eye	41.73 (12.84)	44.77 (13.62)	47.01 (15.03)
Worse-seeing eye	40.38 (10.13)	40.61 (7.90)	42.33 (12.01)
Both eyes	17.89 (14.05)	14.62 (11.72)	10.66 (10.75)
AMD group			
Better-seeing eye	40.38 (22.01)	40.53 (25.99)	46.58 (30.55)
Worse-seeing eye	28.89 (23.47)	25.28 (21.84)	26.04 (22.82)
Both eyes	30.73 (23.51)	34.19 (27.45)	27.39 (21.29)

3.2.2. Rivalry rate

Rivalry rate (number of image alternations per minute) was analyzed with Group as the between-subjects variable, Contrast (high, medium, and low), and Eye (better-seeing eye, worse-seeing eye) as within subject variables. The Group ($F(2, 48) = 41.43$, $p < .05$) and Contrast ($F(2, 47) = 16.52$, $p < .05$) effects were significant but not that of Eye or any interaction. The rivalry rate means and standard errors at the three levels of contrast for the three groups are presented in Fig. 7.

The results showed that the rivalry rates of the better-seeing eye were not significantly different from the rivalry rates of the worse-seeing eye. Rivalry rates at high contrast were significantly higher than those at medium contrast ($p < .05$), and both were higher than rivalry rates at low contrast ($p < .05$). Post hoc tests of the significant Group effect showed that the rivalry rates of both control groups were significantly higher than those of the AMD group.

3.2.3. Interocular acuity differences and rivalry relationships

The correlation between the interocular acuity differences and the worse-seeing eye's time dominance, collapsed over the three contrasts, was significant for the AMD group ($r(49) = -.467$, $p < .001$), but not for the other two groups (Fig. 8). No other correlations between interocular acuity differences and any of the following variables: better-seeing eye time dominance, both eyes time dominance, rivalry rate, or BR were significant.

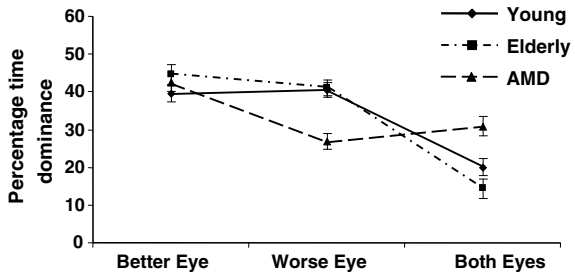

Fig. 6. Mean percentages of eye dominance in the rivalry test with data collapsed over the three contrast levels. (±1 SE.)

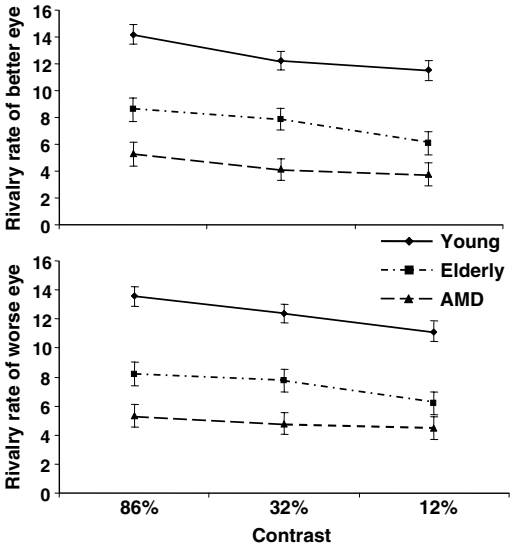

Fig. 7. Mean rivalry rate for the better-seeing eye and the worse-seeing eye at three levels of contrast for the young control, elderly control, and AMD group. (±1 SE.)

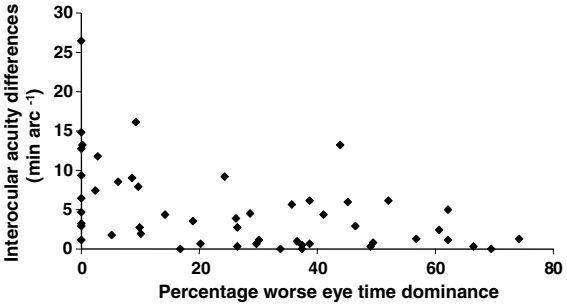

Fig. 8. Percentage worse-seeing eye time dominance as a function of interocular acuity differences for AMD group, with data collapsed over the three contrast levels.

3.2.4. Stereopsis analysis

There was no significant correlation between stereopsis and BR, or between stereopsis and rivalry rates for the young and the elderly control groups. Likewise, there was no relationship between stereopsis and rivalry rates for the AMD group, but there was a strong, negative correlation between stereopsis and BR at high contrast (Pearson $r = -.856$, $p < .005$). We are cautious interpreting these results because stereopsis was measured with the Titmus test, which offers a coarse measurement of stereo acuity.

We further split the AMD group into a stereopsis (Group 1—stereopsis better than or equal to 800 s) and no stereopsis (Group 2—stereopsis worse than 800 s) based on the Titmus test values to evaluate whether their BR and rivalry rates differed. Our analysis showed that there was no difference between the BR of the patients with or without stereopsis, or between their respective rivalry rates. The stereopsis of patients with AMD is a topic we want to explore in further research.

4. Discussion

The binocular function of people with AMD has been investigated in only two studies both of which focused primarily on binocular contrast summation (Faubert & Overbury, 2000; Valberg & Fosse, 2002). The present study was the first, to our knowledge, that studied binocular acuity summation and rivalry in people with AMD.

In Experiment 1 we found that best monocular and binocular acuity of the patients with AMD were significantly lower than those of the young and elderly control groups at high, medium, and low contrasts. Loss of acuity is a characteristic of the disease, because AMD affects the part or the retina with the highest concentration of cones. The acuities of the patients with AMD however, were not as low as those recorded with the ETDRS in the clinic. Our computerized tumbling E acuity test facilitated the performance of the patients with AMD. Indeed, the test recorded a mean visual acuity more than 4 min of arc (or three ETDRS lines) better than that recorded clinically with conventional tests and this result is consistent with that of Harris et al. (1985). The acuity values measured here may have been further enhanced by the fact that our test presents the optotypes in reverse polarity. Westheimer (2003) found that acuity measured with Landolt C test using light letters on a dark background is significantly improved when compared with a test using the opposite polarity, because glare and light scatter are reduced. Taken together, we were able to provide optimal testing conditions, which resulted in a better acuity performance by the patients with AMD.

One may argue that probability summation may explain the superiority of the multiple tumbling E over the classical acuity test. Depending on the state of the disease, its duration and other factors, patients with age-related macular degeneration frequently exhibit gaze selection and control problems which can severely underestimate acuity when measured with standard charts. An error of gaze selection or control of only 5 min arc could reduce the Snellen acuity of a person from 20/20 to 20/40 (Regan, Giaschi, Kraft, & Kothe, 1992). The increase in measured acuity with a multiple optotype chart over a standard chart can only be attributed to probability summation when the patient's gaze control and selection are normal. The objective behind the repeat multiple E charts, such as Harris et al.'s and the one used here, is to stimulate many retinal areas simultaneously and thus obtain a measure of the optimal visual acuity a person is capable of. Viewed in this light, these multiple optotype tests are useful tools for rehabilitation purposes.

A different kind of multiple optotype test was developed by Regan et al. (1992) for testing people with amblyopia. It shows multiple identical letters in the centre of the chart and different letters in the periphery. Our multiple E test does share a problem with standard charts such as the EDTRS in that optotypes towards the edges, adjacent to a blank field, are less affected by lateral interactions or masking than those within the array and produce better performance for people suffering from the effects of crowding

(Shapiro, 1971). This is avoided in Regan's repeat letter chart by surrounding the targets with other letters, which also reduces the effects of probability summation. However, the Regan repeat letter chart was designed as a method of testing people with amblyopia who suffer from deficient gaze selection and or control, but who, nevertheless, have intact maculas. Since the critical optotypes are in the centre, the Regan repeat letter charts, despite their advantages, could be confusing for a person with a diseased macula who has not yet learned to fixate eccentrically or has poor fixation stability.

It is obvious that the pathology severely impaired both the monocular and binocular acuity of the patients, but it is interesting that the three groups were similar in the sense that, for each group, binocular acuity was not significantly different from monocular acuity, at any of the contrast levels. The implications of this result are discussed shortly.

The finding that acuity declines at low contrast has been repeatedly and consistently reported (Cagenello et al., 1992; Gilchrist & Pardhan, 1987; Ross et al., 1985). In the present study, the elderly and young control groups showed a significant, but mild decrease, while the AMD group showed a steep decline in acuity when contrast was reduced (see Fig. 2). Acuity was also affected by age alone. The elderly control group had lower acuity than the young control group at all three levels of contrast. This result was expected on the grounds that age affects most visual structures and functions (Faubert, 2002).

Binocular gain (calculated as a binocular ratio) at high contrast was 12% for the young control group. This is consistent with previous findings that showed a binocular acuity gain between 9% and 11% (Frisen & Lindblom, 1988; Heravian et al., 1990; Home, 1978; Horowitz, 1949). The acuity gain of the elderly control group was 2% and that of the AMD group was 5% at high contrast. Despite the fact that these mean values were smaller than that of the young control group the differences were non-significant. Although our sample size may have prevented us from finding a significant effect, our data are consistent with other reports in the literature. For instance, Gagnon and Kline (2003) also reported that older participants had a smaller binocular acuity ratio than younger participants, but the difference was not significant. Rubin et al. (2000) examined binocular acuity gain of a large sample of older observers and found a smaller binocular gain than that reported previously in the literature, both for observers with similar acuities in both eyes and for those with unequal acuities. In addition, binocular gain did not vary with contrast for any of the groups. These results contradict our prediction that the AMD group would have a smaller binocular ratio. We found that the binocular acuity summation function was preserved in people with AMD. It is surprising that the visual system of patients with AMD maintains its ability to combine the inputs from the two eyes, resulting in a binocular gain similar to that of normally sighted observers because, typically, AMD does not affect the two eyes equally, and the two monocular acuities often differ considerably. Also, unequal scotomas in the two eyes produce disproportionate stimulation of the two retinas and loss of fixation stability. Because our acuity test does not require stable fixation, and because it facilitates the use of peripheral vision, we were able to obtain an average of 5% binocular improvement at the three contrasts for the AMD patients.

The mean binocular gain of the young participants who experienced summation was 27%, that of the elderly participants 16% and that of patients 22%. These values were not significantly different from each other. One may be tempted to conclude that this binocular gain can be explained with a probability summation model because the values are within those predicted with such a model. While this may be true for the young and elderly control groups, we are cautious about drawing this conclusion for the AMD group because the probability summation model is based on the assumption that the sensitivities of the two eyes are similar and this is not the case for most patients with AMD. However, data for the AMD group, who had higher interocular acuity differences than the young group, fit well with Rubin et al.'s (2000) findings that showed that 20–29% of older people with dissimilar acuities in the two eyes experienced acuity summation. Interestingly, the binocular loss of the observers who experienced inhibition was almost identical for the three groups (14% for the young group and 15% for the elderly and AMD groups). These findings suggest that age and AMD do not affect the amount of binocular acuity summation and inhibition.

Consistent with previous studies, we found a high percentage of AMD patients who showed inhibition (39%). The elderly group showed a similar proportion (33%), whereas the proportion for the young control group was lower (24%). Faubert and Overbury (2000), and Valberg and Fosse (2002) found a higher proportion of AMD participants who experienced contrast inhibition on detection tasks than controls, but their control groups were much younger or smaller in size. They concluded that AMD may be the cause of the high proportion of patients who demonstrated inhibition. The authors explained their findings by the fact that the disease damages the retinas of the two eyes unequally, producing differences in luminance levels. This is similar to Fechner's Paradox, which shows that binocular inhibition occurs when the two eyes are unequally illuminated (Howard, 2002). In addition, Valberg and Fosse (2002) concluded that "the explanation of binocular inhibition lies in the application of non-corresponding retinal areas for binocular viewing" (p. 227). Our data showed a large incidence of inhibition in the elderly control group as well. We think that if we had had an age-matched control group rather than a younger elderly control group, the proportion of the inhibition cases in the AMD and age-matched control groups would probably have been even closer.

In Experiment 2 we found that rivalry time dominance was independent of contrast for all three groups. The mean

time dominance of the better-seeing eye was not different from that of the worse-seeing eye for the young and elderly groups. On the contrary, the mean time dominance of the better-seeing eye was higher than the mean time dominance of the worse-seeing eye for the AMD group; however, the mean time dominance of the better-seeing eye of the AMD group was similar to that of the young and elderly control groups. Typically, the disease affects the two eyes unequally, resulting in large differences between the acuities of the two eyes. Interestingly, however, the mean time dominance of the better-seeing eye did not exceed that of the elderly or young controls. This result is consistent with Levelt's (1966) proposition that increasing the stimulus strength in one eye has little effect on its own time dominance, but affects the suppression time of the other eye. Based on these results, we may conclude that the better-seeing eye's time dominance is not affected by age or pathology.

The mean time dominance of the piecemeal image (both eyes at the same time) was higher for the AMD group than for the other two groups (see Fig. 6). In people with healthy retinas, research has shown that piecemeal rivalry is more common with large targets (Howard, 2002). It is also known that contours arising from both modal or filling-in (He & Davis, 2001; Tong & Engel, 2001) and amodal completion or cognitive contours can produce rivalry (Fahle & Palm, 1991; Harris & Gregory, 1973; Sobel & Blake, 2003). In addition to their mostly peripheral vision, we do not know what role the abnormal, reduced, or absent retinal input from the—perhaps non-corresponding parts—of the patients' retinas play in their binocular rivalry. The explanation of these results requires further research but, regardless of the answer, it seems that pathology disrupts time dominance during rivalry, whereas age alone does not.

Rivalry rates decreased with age and contrast. This result is consisted with that of Ukai et al. (2003) who found that rivalry rates decrease with age. The AMD group had the lowest rivalry rates, followed by the elderly control group. Because our elderly control group was younger than the AMD group, one may be reluctant to conclude that lower rate observed in the AMD group was due to the disease rather than the result of age. We suspect, however, that the low rivalry rate recorded for the patients with AMD is at least partly due to the disease. This is because, unlike the normally sighted controls, patients with AMD make use mainly of their eccentric vision, and it has been shown that rivalry rates decrease with increased eccentricity (Blake et al., 1992). In addition, we looked at the covariance of age for the elderly controls and AMD group and found that the effect of age was very small (.09), whereas the effect of the disease was much higher (.24).

Finally, high interocular acuity differences were negatively correlated with the rivalry time dominance of the worse-seeing eye for the AMD group. This result suggests that the large differences in monocular acuities commonly found in people with AMD do not affect BR, but may disrupt rivalry dominance.

A few limitations of this study must be acknowledged. First, despite our efforts, we failed to provide an age-matched control group; instead, our elderly group had a mean age seven years younger than the AMD group. While this difference is not very large, it was enough to reach significance. It was very difficult to find volunteers older than eighty years of age with no ocular disease. Second, despite the fact that, overall, the differences between binocular and best monocular tests were not significant for any of the three groups, it should be noted that our tests of monocular acuity were performed with the observers wearing a black eye patch. The effects of interocular brightness and frequency content differences on binocular performance are well documented (e.g., Campbell & Green, 1965; Home, 1978; Horowitz, 1949; Pardhan & Gilchrist, 1990; Wildsoet, Wood, Maag, & Sabdia, 1998). Other factors, such as unstable monocular accommodation, could have increased the measurement noise. Third, the results of this study do not provide information about how dry and wet forms of the disease affect binocular function. Thus, our conclusions are limited to general statements about how AMD affects binocular function rather than being specific to the subtypes of the disease. We think however, that it is probably the stage of the disease rather than the type that affects binocular function because the effect of the disease is the same: macular damage and loss of central vision.

It would be beneficial to strengthen our suggestion that age rather than disease affects the number of people exhibiting inhibition by using a control group closer in age to the AMD group. In addition, we are in the process of measuring binocular gain with an acuity test that requires the identification of single optotypes.

5. Conclusions

The present study explored how binocular function is affected in people with AMD. We found that neither the disease, nor age affected binocular ratio, the amount of binocular inhibition, or the amount of binocular summation. The proportion of AMD patients who experienced inhibition was higher than that of the young control group. Rivalry rates were affected by age, and further by pathology. Surprisingly, the better-seeing eye time dominance of the AMD group was not different from that of the young or elderly control group. The worse-seeing eye time dominance however, was significantly lower, and the piecemeal dominance was significantly higher than those of the other two groups. Since the young and elderly control groups did not differ, we suggest that these differences were solely due to the disease. Thus, we conclude that rivalry processes are disrupted in people with AMD.

Acknowledgments

Supported by Natural Science and Engineering Research Council Grant A7664, the Vision Science Research Program

at the Toronto Western Hospital, the Jackman Foundation, the Sir Jules Thorn Charitable Trust and The Krembil Family Foundation. The authors thank Linda Lillakas for technical assistance and editing of the manuscript.

References

Azen, S. P., Varma, R., Preston-Martin, S., Ying-Lai, M., Globe, D., & Hahn, S. (2002). Binocular visual acuity summation and inhibition in an ocular epidemiological study: The Los Angeles Latino eye study. *Investigative Ophthalmolology and Visual Science, 43*, 1742–1748.

de Belsunce, S., & Sireteanu, R. (1991). The time course of interocular suppression in normal and amblyopic subjects. *Investigative Ophthalmology and Visual Science, 32*, 2645–2652.

Blake, R., & Fox, R. (1973). The psychophysical inquiry into binocular summation. *Perception & Psychophysics, 14*, 161–185.

Blake, R., & Logothetis, N. K. (2002). Visual competition. *Nature Reviews. Neuroscience, 3*, 1–11.

Blake, R., O'Shea, R. P., & Mueller, T. J. (1992). Spatial zones of binocular rivalry in central and peripheral vision. *Visual Neuroscience, 8*, 469–478.

Bullimore, M. A., Bailey, I. L., & Wacker, R. T. (1991). Face recognition in age-related maculopathy. *Investigative Ophthalmology and Visual Science, 32*, 2020–2029.

Cagenello, R., Arditi, A., & Halpern, D. L. (1992). Binocular enhancement of visual acuity. *Journal of the Optical Society of America, 10*, 1841–1848.

Campbell, F. W., & Green, D. G. (1965). Monocular versus binocular visual acuity. *Nature, 208*, 191–192.

Edwards, M. G., Bressler, N. M., & Raja, S. C. (1999). *Ophthalmology* (1st ed.). London: Mosby International Ltd.

Elliott, D. B., Patla, A. E., Flanagan, J. G., Spaulding, S., Rietdyk, S., Strong, G., et al. (1995). The Waterloo vision and mobility study: Postural control strategies in subjects with ARM. *Ophthalmic and Physiological Optics, 15*, 553–559.

Ergun, E., Maar, N., Radner, W., Barbazetto, I., Schmidt-Erfurth, U., & Stur, M. (2003). Scotoma size and reading speed in patients with subfoveal occult choroidal neovascularization in age-related macular degeneration. *Ophthalmology, 110*, 65–69.

Eye Disease Prevalence Research Group, 2004. Causes and prevalence of visual impairment among adults in the United States. *Archives of Ophthalmology*, 122, 477–485.

Fahle, M., & Palm, G. (1991). Perceptual rivalry between illusory and real contours. *Biological Cybernetics, 66*, 1–8.

Faubert, J. (2002). Visual perception and ageing. *Canadian Journal of Experimental Psychology, 56*, 164–176.

Faubert, J., & Overbury, O. (2000). Binocular vision in older people with adventitious visual impairment: Sometimes one eye is better than two. *Journal of American Geriatrics Society, 48*, 375–380.

Frisen, L., & Lindblom, B. (1988). Binocular summation in humans: Evidence for a hierarchic model. *Journal of Physiology, 402*, 773–782.

Gilchrist, J., & Pardhan, S. (1987). Binocular contrast detection with unequal monocular illuminance. *Ophthalmic and Physiological Optics, 7*, 373–377.

Gagnon, R. W., & Kline, D. W. (2003). Senescent effects on binocular summation for contrast sensitivity and spatial interval acuity. *Current Eye Research, 27*, 315–321.

González, E. G., Markowitz, S. N., Steinbach, M. J. (2004). *Vision loss from macular degeneration: An optimal way to measure what remains*. Poster session presented at the University Health Network Research Day, Toronto.

Harris, J. P., & Gregory, R. L. (1973). Fusion and rivalry of illusory contours. *Perception, 2*, 235–247.

Harris, M. J., Robins, D., Dieter, J. M., Fine, S., & Guyton, D. L. (1985). Eccentric acuity in patients with macular disease. *Ophthalmology, 92*, 1550–1553.

Hassan, S. E., Lovie-Kitchin, J. E., & Woods, R. L. (2002). Vision and mobility performance of subjects with age-related macular degeneration. *Optometry and Vision Science, 79*, 697–707.

He, S., & Davis, W. L. (2001). Filling-in at the natural blind spot contributes to binocular rivalry. *Vision Research, 41*, 835–840.

Heravian, J., Jenkins, T., & Douthwaite, W. A. (1990). Binocular summation in visually evoked responses and visual acuity. *Ophthalmic and Physiological Optics, 10*, 257–261.

Home, R. (1978). Binocular summation: A study of contrast sensitivity, visual acuity and recognition. *Vision Research, 18*, 579–585.

Horowitz, M. W. (1949). An analysis of the superiority of binocular over monocular visual acuity. *Journal of Experimental Psychology, 39*, 581–596.

Howard, I. (2002). *Seeing in depth. Basic mechanisms*, (Vol. I.). Toronto: University of Toronto Press.

Legge, G. E. (1984). Binocular contrast summation—I. Detection and discrimination. *Vision Research, 24*, 373–383.

Levelt, W. J. M. (1966). The alternation process in binocular rivalry. *British Journal of Psychology, 57*, 225–238.

Levitt, H. L. (1971). Transformed up–down methods in psychophysics. *Journal of the Acoustical Society of America, 49*, 467–477.

Liu, L., Tyler, C. W., & Schor, C. M. (1992). Failure of rivalry at low contrast: Evidence of a suprathreshold binocular summation process. *Vision Research, 32*, 1471–1479.

Pardhan, S. (1996). A comparison of binocular summation in young and older patients. *Current Eye Research, 15*, 315–319.

Pardhan, S. (1997). A comparison of binocular summation in the peripheral visual field in young and older patients. *Current Eye Research, 16*, 252–255.

Pardhan, S., & Gilchrist, J. (1990). The effect of monocular defocus on binocular contrast sensitivity. *Ophthalmic and Physiological Optics, 10*, 33–36.

Pardhan, S., Gilchrist, J., Douthwaite, W., & Yap, M. (1990). Binocular inhibition: Psychophysical and electrophysiological evidence. *Optometry and Vision Science, 67*, 688–691.

Pardhan, S., & Whitaker, A. (2000). Binocular summation in the fovea and peripheral field of anisometropic amblyopes. *Current Eye Research, 20*, 35–44.

Pardhan, S., & Whitaker, A. (2003). Binocular summation to gratings in the peripheral field in older subjects is spatial frequency dependent. *Current Eye Research, 26*, 297–302.

Quillen, D. A. (2001). Effect of unilateral exudative age-related macular degeneration on binocular visual function. *Archives of Ophthalmology, 119*, 1725–1726.

Regan, D., Giaschi, D. E., Kraft, S. P., & Kothe, A. C. (1992). Method for identifying amblyopes whose reduced line acuity is caused by defective selection and/or control of gaze. *Ophthalmic and Physiological Optics, 12*, 425–432.

Ross, J. E., Clarke, D. D., & Bron, A. J. (1985). Effect of age on contrast sensitivity function: Uniocular and binocular findings. *British Journal of Ophthalmology, 69*, 51–56.

Rosser, D. A., Cousens, S. N., Murdoch, I. E., Fitzke, F. W., & Laidlaw, D. A. H. (2003). How sensitive to clinical change are ETDRS logMAR visual acuity measurements. *Investigative Ophthalmology and Visual Science, 44*, 3278–3281.

Rubin, G. S., Muñoz, B., Bandeen-Roche, K., West, S. K. for the SEE Project Team (2000). Monocular versus binocular visual acuity as measures of vision impairment and predictors of visual disability, *Investigative Ophthalmology and Visual Science 41*, 3327–3334.

Shapiro, M. (1971). *Amblyopia*. Chilton: PA.

Sobel, K. V., & Blake, R. (2003). Subjective contours and binocular rivalry suppression. *Vision Research, 43*, 1533–1540.

Tejeria, L., Harper, R. A., Artes, P. H., & Dickinson, C. M. (2002). Face recognition in age related macular degeneration: Perceived disability, measured disability, and performance with a bioptic device. *British Journal of Ophthalmology, 86*, 1019–1029.

Tong, F., & Engel, S. A. (2001). Interocular rivalry revealed in the human cortical bind-spot representation. *Nature, 411*, 195–199.

Ukai, K., Ando, H., & Kuze, J. (2003). Binocular rivalry alternation rate declines with age. *Perceptual and Motor Skills, 97*, 393–397.

Valberg, A., & Fosse, P. (2002). Binocular contrast inhibition in subjects with age-related macular degeneration. *Journal of the Optical Society of America, 19*, 223–228.

Westheimer, G. (2003). Visual acuity with reversed-contrast charts: Theoretical and psychophysical investigations. *Optometry and Vision Science, 80*, 745–748.

Wildsoet, C., Wood, J., Maag, H., & Sabdia, S. (1998). The effect of different forms of monocular occlusion on measures of central visual function. *Ophthalmic and Physiological Optics, 18*, 263–268.