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Ocular prevalence and stereoacuity[1]

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Abstract

Background: Most people attribute a higher weight to the input from one eye than to that from the other eye when they have to align stereodisparate objects in the same visual direction. This preference for visual directions has been termed 'ocular prevalence', according to the Latin praevalentia = superior power. Questions: (1) Is ocular prevalence of one eye (or its correlate, partial suppression of the other eye in the prevalence task) restricted to large stereodisparities, close to Panum's limit, or does it occur also at small stereodisparities, near the stereoscopic threshold? (2) Is ocular prevalence a handicap for stereoacuity?

Methods: Six non-strabismic observers with equal visual acuity of their two eyes were examined. To determine their ocular prevalence, they were presented with vertical vernier lines at stereodisparities ranging between 30 and 430 arcsec. They had to judge whether the lower, anterior line was located on the right- or left-hand side of the upper, posterior line. Their stereoscopic threshold was measured with an adaptive staircase procedure, using the Freiburg Stereoacuity Test.

Results: All six observers exhibited some ocular prevalence. It changed considerably on repeated measurements. In three observers, it even switched from one eye to the other. Ocular prevalence occurred not only at large stereodisparities, close to Panum's limit, but also at small stereodisparities. The stereoscopic threshold of the six observers ranged between 1.7 and 12.3 arcsec.

Conclusion: Ocular prevalence is common, intra-individually variable and occurs even at small stereodisparities close to the stereoscopic threshold. It is compatible with 'optimal' stereoacuity. Hence, ocular prevalence appears to be a harmless feature of normal binocular vision.

Keywords: fixation disparity, ocular prevalence, stereoacuity

Introduction

Aligning stereodisparate objects to the same visual direction is difficult, because different inputs, transmitted from the two eyes, have to be processed. For this task, most people attribute a higher weight to the input from one eye than to that from the other eye (Sachsenweger, 1958; Haase, 1995; Erkelens *et al*., 1996; Kommerell *et al*., 2003). This preference for relative visual directions was termed 'ocular prevalence' by Sachsenweger (1958), and this term has since been adopted by several authors (Haase, 1995; Kommerell *et al*., 2003; Heinrich *et al*., 2005; Ehrenstein *et al*., 2005). To avoid any misunderstanding: 'prevalence' is used here in the original sense of the Latin praevalentia = superior power, and does not mean 'the percentage of cases in a certain population'.

Ocular prevalence should be distinguished from ocular dominance (Kommerell *et al*., 2003). Ocular dominance is determined by subjective alignment of two objects presented at a stereodisparity far beyond Panum's area. A typical test is to align a small hole in a hand-held card with a distant target. Such tests reveal the habit or ease of using one eye for monocular tasks (Mapp *et al*., 2003). They force subjects to decide in favour of one or the other eye. In contrast, ocular prevalence is determined by the alignment of two objects presented inside Panum's area. These tests allow a graded quantification of the balance between the eyes

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[a graded quantification is also possible on the basis of binocular rivalry (e.g. Ooi and He, 2001; Handa *et al.*, 2004)].

Haase (1995) suggested that ocular prevalence could be due to fixation disparity. According to his hypothesis, the eye that contributes less to the binocular percept points slightly beside the fixation target. Haase further postulated that the presumed fixation disparity, implying eccentric imaging of the target in one eye, impairs stereoacuity. However, recordings of the eye position with the search coil technique have disproved the notion that ocular prevalence indicates fixation disparity (Gerling *et al.*, 2000). Moreover, preliminary studies have shown that ocular prevalence, present at a large stereodisparity near the border of Panum's area, is compatible with a stereoscopic threshold as small as 15 arcsec (Kromeier *et al.*, 2002).

The purpose of the present study was to examine the relationship between ocular prevalence and stereoscopic resolution in more detail. Originally, we hypothesised that ocular prevalence might exist only at the border of Panum's area and might disappear at small disparities (Kommerell *et al.*, 2003). According to this preliminary hypothesis, ocular prevalence extends the range of binocular single vision towards large stereodisparities by a partial suppression of one eye. Our preliminary hypothesis further suggested that absence of ocular prevalence at small stereodisparities (implying an equal contribution of both eyes to perceived visual directions) might be a prerequisite for optimal stereoacuity. To our surprise, the present study revealed that ocular prevalence occurs also in tasks involving very small stereodisparities without degrading stereoacuity.

Methods

Observers

Six observers (employees of our department or students of medicine, aged between 22 and 34 years, median 27 years) were selected according to the following three criteria: (1) visual acuity (with spherical and cylindrical spectacle correction) for numerical optotypes at least 1.0 (=6/6) in each eye; (2) difference between the visual acuities of the two eyes not more than by a factor of 1.26 (approximately 0.1 log units); and (3) absence of strabismus, ascertained with the unilateral cover test.

Phoria at distance: the alternate cover test revealed that observer KB had 2Δ base out; the other five observers had ±0. *Refraction*: three observers had no ametropia or a minimal myopia (up to −0.50); observer PM had myopia of about −1.50; observer KB about −3.50; and observer SH about −8.50 (he was wearing contact lenses).

We explained to the observers that the study was designed to measure the contribution of each eye to their binocular vision. Otherwise, the observers were naive as to the purpose of the study. Each observer provided informed written consent to participate in the experiments. The study followed the tenets of the Declaration of Helsinki and was approved by the local ethics review board.

Ocular prevalence

The stimulus was generated by a PowerMacintosh G4 and presented at a distance of 4.5 m on a Philips GD403 CRT monitor. By means of liquid crystal shutter goggles (ELSA 3D Revelator: Elsa Technology, Wurselen, Germany), separate images were presented to the two eyes. The goggles were synchronised to the CRT refresh such that the frames were alternately presented to the right and left eyes. The refresh rate of 120 Hz resulted in a rate of 60 Hz for each eye, just above the flicker fusion frequency.

The stimulus consisted of two vertical vernier lines, one above the other (*Figure 1*). The lines had a width of 4.5 arcmin and a height of 19.8 arcmin. They were separated by a vertical gap of 4.5 arcmin. A frame with a height of 69 arcmin, a horizontal extension of 92 arcmin and a thickness of 1.4 arcmin surrounded the lines. To stabilise vertical fusion, the frame was divided in the middle by a horizontal bar of 1.4 arcmin thickness. A binocular pattern with random black and white squares with an edge length of 3 arcmin surrounded the frame. The luminance of the 'black' areas on the monitor was 1.8 cd/m^2, and the luminance of the 'white' areas was 40 cd/m^2.

The upper line was located in the same plane as the surrounding pattern. The lower line was presented at five discrete stereodisparities (30, 62, 130, 270 and 430 arcsec) such that it appeared closer to the observer than the upper line and the frame. All six observers were tested with stereodisparities of 30, 270 and 430 arcsec. Four of the observers were also tested with 62 and 130 arcsec. At each stereodisparity, the lower line was shown with a variable lateral offset, either to the right or to the left of the upper line. The smallest step for the lateral offset was 8.5 arcsec.

In a two-alternative forced-choice task, observers had to indicate, by pressing the appropriate one of two buttons, whether they perceived the lower line to the right or to the left of the upper line. If either the upper or the lower line appeared double, observers were told to base their judgement on the centre between the doubled line. We did not instruct the observers to fixate either the upper (posterior) or the lower (anterior) line. The frame and the vernier lines remained in place until the observers had pressed one of the two buttons. After an

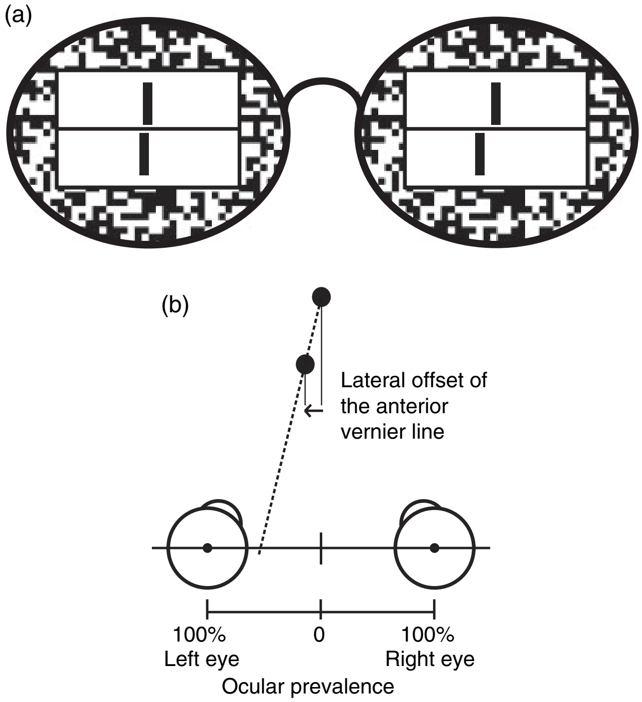

Figure 1. Stimulus condition. (a) Observer's view. The upper (posterior) vernier line and the frame are shown in the plane of the CRT monitor at 4.5 m. The lower (anterior) vernier line appears at discrete stereodisparities in front of the CRT monitor, with a variable lateral offset. (b) View from above. The lateral offset at which the observer perceives the two vernier lines as being aligned defines the individual's ocular prevalence. The line that connects the posterior and the anterior objects crosses the interocular line. Depending on the crossing point, ocular prevalence can vary between 100% prevalence of the left eye and 100% prevalence of the right eye. A prevalence of 0% means that both eyes contribute equally to the visual directions. The figure shows an example of an observer who has a 50% prevalence of the left eye.

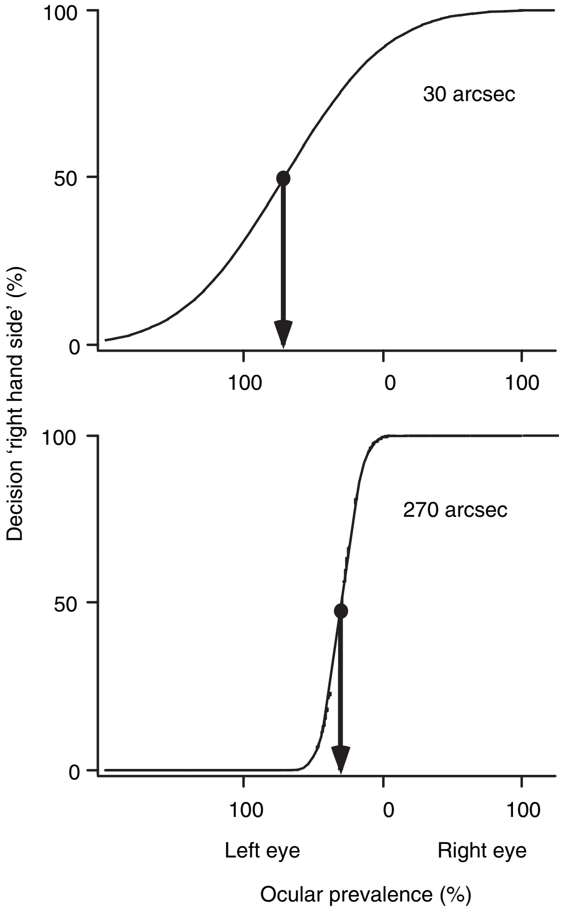

Figure 2. Psychometric functions of the right/left decision in relation to the physical offset of the anterior object (observer SH at the stereodisparities of 30 and 270 arcsec). Filled circle: 50% = point of subjective alignment.

interval of 0.5 s, in which the whole field was filled by the random black and white squares, the frame and the vernier lines appeared again. The observers wore an appropriate spherical and cylindrical correction. None of them had a prismatic correction. (*Note*: although a prism should have altered the effective interpupillary distance, neither the stereodisparity of the vernier lines nor their lateral offset would have been affected because the stimuli were haploscopically projected onto the retinae.) The observers looked at the stimuli with their trunk and head directed straight ahead.

To accustom the observers to the procedure, two training blocks with a stereodisparity of 30 and 430 arcsec, respectively, preceded the actual experiment.

To balance sequential (e.g. learning) effects, we randomised the order of the stereodisparities between observers.

At each stereodisparity, a psychometric function was derived from a block of 160 trials (*Figure 2*). To save time, each block started with 10 trials in which the location of the 50% point was estimated based on a coarse variation of the lateral offset. This value was then used as the starting point for three randomly interleaved staircase procedures, targeting (according to a variant described by Leek, 2001) the 21, 50 and 79% probability of the 'right-hand side' response with the remaining 150 trials. Combining the trials of all three-staircase procedures, the psychometric function for each stereodisparity was fitted as a cumulative Gaussian by weighted linear regression. Fitting errors were estimated with the bootstrapping procedure suggested by Foster and Bischof (1991); we used their C code provided at http://www.cs.ualberta.ca/~wfb/software.html. The 50% point of the psychometric function was taken as the position at which the two vernier lines appeared aligned.

As depicted in *Figure 1b*, the position in which the near object appears aligned with the far object allows the calculation of ocular prevalence. A 100% prevalence of one eye means that a physical alignment of the objects to that eye is perceived as alignment. Intermediate values between 100% prevalence of the right and 100%

prevalence of the left eye can be read on a linear scale (neglecting the tiny tangent deviation from linearity, due to the stimulus presentation at 4.5 m instead of infinity). The stereodisparity between the far and the near objects determines the factor by which ocular prevalence can be calculated: 1/2 of the stereodisparity corresponds to 100% prevalence of one eye. For example, at the smallest stereodisparity of 30 arcsec, a lateral offset of the anterior object by only 15 arcsec corresponds to 100% ocular prevalence, whereas, at the largest stereodisparity of 430 arcsec, a lateral offset of the anterior object by 215 arcsec corresponds to 100% ocular prevalence.

Across observers, correlation coefficients and regression lines were computed with Igor Pro (Wavemetrics Inc., Lake Oswego, USA).

Before the experiments observers were instructed to attend to two questions: (1) do I have a stereoscopic percept? (2) do I see double (either the anterior or the posterior vernier line)? The observers had to report immediately when the stimulus did not elicit a stereoscopic percept or appeared double. After each block the examiner estimated and noted the percentage of stimuli that the observer had commented with ‘no stereoscopic percept’ and/or with ‘double vision’.

Stereoacuity

We used the Freiburg Stereoacuity Test (Bach *et al*., 2001), presented at 4.5 m with the set-up employed also for the measurement of ocular prevalence.

The stereo target consisted of a vertical bar, surrounded by a frame. To mask monocular clues, the bar was not centred with respect to the frame but placed randomly, trial-by-trial, to the right or left of the centre by the amount of the actual disparity. The distance between the bar and the left or right inner frame edge was three times the disparity. At the viewing distance of 4.5 m, each pixel subtended 20 arcsec. Disparities down to 1 arcsec were implemented via ‘anti-aliasing’.

We used a two-alternative forced-choice paradigm in which the observer had to decide whether the bar appeared in front of or behind the frame. The stimulus disappeared when the observer had made his or her choice by pressing the appropriate one of two buttons. The next stimulus selected by the ‘best PEST’ algorithm (Lieberman and Pentland, 1982) was presented after an interval of 0.5 s, during which the random square pattern covered the whole field. The value reached after 100 trials (one block) were taken as the stereo threshold.

A previous study had shown that some observers markedly improve their performance on repeating the Freiburg Stereoacuity Test (Schmitt *et al*., 2002). To account for this effect, we included in our study only observers who had practiced the Freiburg Stereoacuity Test while taking part in this previous study. Their training consisted of at least three sessions on three consecutive days. Each session consisted of three blocks with an interval between blocks of about 10 min. Thus, each observer attended a minimum of nine blocks. During the last four test sessions, the observers improved their performance very little or not at all.

The data on stereoacuity were obtained several weeks before the data on ocular prevalence.

Results

For disparities up to 130 arcsec, all observers were able to fuse the stereo target without seeing double. At 270 arcsec disparity four of the six observers and at 430 arcsec all observers saw either the anterior or the posterior vernier line double.

All six observers exhibited some ocular prevalence (*Figure 3*). Regarding each observer individually, ocular prevalence changed considerably with the stereodisparity of the stimulus. These changes were significant for all observers ($p < 0.001$) with the exception of PM ($p = 0.051$) (Monte-Carlo simulation). In three observers, ocular prevalence even switched from one eye to the other.

Because of the high variability of the data we looked at the individual reproducibility. We randomly selected two of the six observers (IS and PM), and examined them five times over the whole range of stereodisparities between 30 and 430 arcsec. These experiments took place in a time span of several days. To balance sequential (e.g.

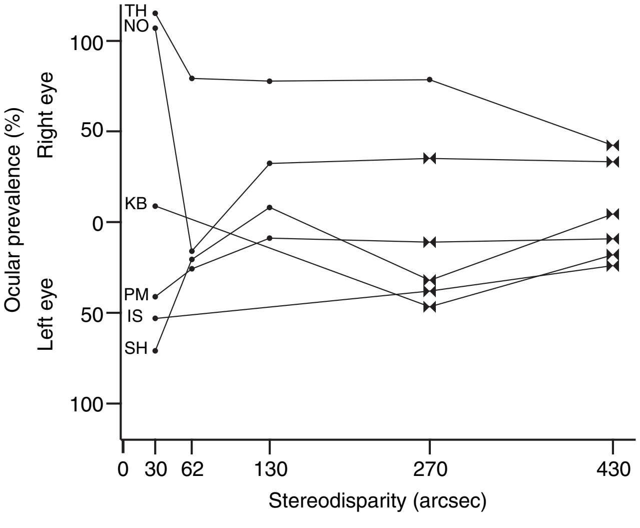

Figure 3. Ocular prevalence in relation to the stereodisparity of the stimulus. The data of each of the six observers are marked with the observer's initials and connected with lines. The bow-tie symbol indicates that the observer reported double vision. It can be seen that ocular prevalence is highly variable.

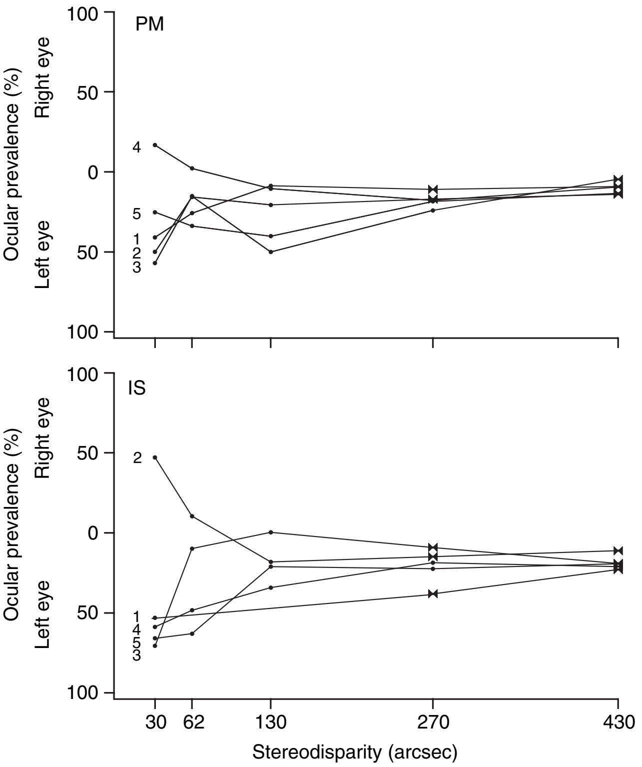

Figure 4. Ocular prevalence of observers PM (top graph) and IS (bottom graph). The data of each of the five runs are connected with lines and marked with the number of the run. The bow-tie symbol indicates that the observer reported double vision.

learning) effects, we randomised the order of the stereodisparities between the five runs. For disparities up to 130 arcsec, both observers were able to fuse the stereo target without seeing double. At 270 arcsec disparity, IS reported double vision in 3, PM in two out of five runs. At 430 arcsec both observers saw either the anterior or the posterior vernier line double. *Figure 4* shows that ocular prevalence scattered considerably.

Pursuing our original hypothesis that ocular prevalence might exist only at the border of Panum's area and might disappear at small disparities (Kommerell *et al.*, 2003), we compared the absolute values of ocular prevalence (neglecting whether the right or the left eye was prevalent) in a spot check. We chose the responses that were not accompanied with 'double vision', i.e. the data obtained at 130 and 30 arcsec. Four observers were eligible (two observers had not been tested at 130 arcsec). Ocular prevalence at 30 arcsec was not smaller than at 130 arcsec, it was even larger ($p = 0.014$, Student's t-test). In the repeated measurements of IS (*Figure 4*), this 'reverse' trend was further substantiated: ocular prevalence was significantly larger at 30 than at 130 arcsec ($p = 0.027$, Student's t-test). In the repeated measurements of PM (*Figure 4*) the difference was not significant ($p = 0.24$, Student's t-test).

The stereoscopic threshold of the six observers ranged between 1.7 and 12.3 arcsec. Across all six observers, the correlation between the stereoscopic threshold and the ocular prevalence was low and far from being significant (30 arcsec: $r = -0.0074$, $p = 0.99$; 270 arcsec: $r = 0.69$, $p = 0.13$; 430 arcsec: $r = 0.48$, $p = 0.34$). The power of this statistical evaluation was: 0.99 for 30 arcsec, 0.65 for 270 arcsec and 0.70 for 430 arcsec. This means that for 270 and 430 arcsec the probability of a false-negative result is low, and for 30 arcsec it is negligible.

Our original hypothesis suggested that ocular prevalence or its correlate (partial suppression of one eye in the prevalence task) might impair stereoacuity especially at small stereodisparities. To test this hypothesis, we present the data on ocular prevalence obtained at 30 arcsec in detail (*Figure 5*) and show their relationship to the stereoscopic threshold. It can be seen that, contrary to our original hypothesis, a considerable ocular prevalence is compatible with a very high stereoacuity. For example, observer IS had an ocular prevalence of 53% and a stereoscopic threshold of 1.7 arcsec.

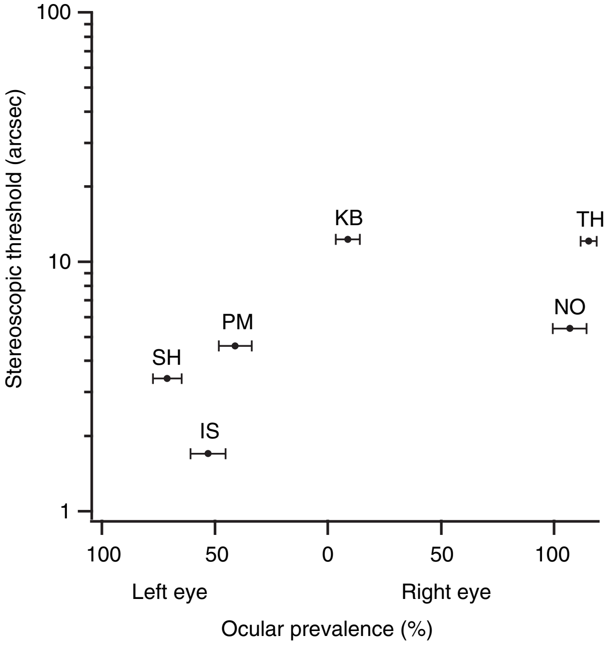

Figure 5. Stereoscopic threshold in relation to ocular prevalence (at a stereodisparity of 30 arcsec). The bars represent the fitting errors of the psychometric functions as estimated with a bootstrapping procedure, i.e. the precision with which ocular prevalence was determined (see Methods). The six observers are identified by their initials. In the two observers who were tested repeatedly (PM and IS) the values of the first run are shown. It can be seen that, across all six observers, the correlation between the stereoscopic threshold and the ocular prevalence is low, and even a very small stereoscopic threshold can be associated with a marked ocular prevalence.

Discussion

All our six observers showed some ocular prevalence. Of particular interest is that prevalence of one eye (or its correlate, partial suppression of the other eye in the prevalence task) occurred not only at large, but also at small stereodisparities, without impairing stereoacuity. When the stereodisparity between the far and near objects was 30 arcsec, four of the six observers had an ocular prevalence of more than 50% (*Figure 3*). Nevertheless, all six observers had stereoscopic thresholds between 1.7 and 12.3 arcsec, which is close to the established optimum (Westheimer *et al*., 1980). The correlation between the stereoscopic threshold and the ocular prevalence, measured at the various stereodisparities, was far from being significant.

Such small stereoscopic thresholds are not conceivable without a near-to-equal contribution of both eyes. Hence, we conclude that the partial suppression of one eye that occurs in the ocular prevalence task does not affect stereoscopic resolution. Rather, the partial suppression of one eye is confined to the judgement of relative visual directions between objects presented at different depth planes. Thus, it appears that the two capabilities, stereoscopic discrimination and the assessment of visual directions in the three-dimensional world are based on independent mechanisms.

Although ocular prevalence is well defined in single determinations of the psychometric function (see the small error bars in *Figure 5*), it can scatter over a wide range on repeated measurements from day-to-day, both at the same stereodisparity and across various stereodisparities. For example, observer SH showed 8% prevalence of the right eye when tested at the stereodisparity of 130 arcsec and 71% prevalence of the left eye when tested at the stereodisparity of 30 arcsec.

How can the variability of ocular prevalence be explained? To determine the relative visual directions of objects in different depth planes with two eyes requires a complicated computation of the inputs from the two eyes. We speculate that the brain does not care to solve this task with great accuracy because, during evolution, the advantage for survival would have been low. According to this speculation, the brain simply accepts that the vantage point between the eyes is variable. It also accepts that the precision for relative visual directions decreases with increasing stereodisparity. We have shown this in a parallel investigation, studying the vernier acuity for stereodisparate objects (Heinrich *et al*., 2005). For the rare situations in which an exact alignment between far and near objects is necessary, humans resort to monocular vision by closing one eye, for instance when aiming a rifle.

Based on the intra-individual variability and the compatibility with excellent stereoacuity, we conclude that ocular prevalence is a harmless feature of normal binocular vision.

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