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Assessing Binocular Advantage in Aided Vision

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14. ABSTRACT Advances in microsensors, microprocessors and microdisplays are creating new opportunities for improving vision in degraded environments through the use of head-mounted displays. Initially, the cutting-edge technology used in these new displays will be expensive. Inevitably the cost of providing the additional sensor and processing required to support binocularity brings the value of binocularity into question. The value of binocularity in human vision is well documented, yet the value of binocularity in sensor/display systems for aided vision is controversial. Several assessments comparing binocular, biocular and monocular head-mounted displays for aided vision have concluded that the additional performance, if any, provided by binocular head-mounted displays does not justify the cost. It is possible that the human binocularity advantage doesn't carry over to the aided vision application, but more likely the experimental approaches used in the past have been too coarse to measure its subtle but important benefits. Evaluating the value of binocularity in aided vision applications requires an understanding of the characteristics of both human vision and head-mounted displays. With this understanding, the value of binocularity in aided vision can be estimated and experimental evidence can be collected to confirm or reject the presumed binocular advantage, enabling improved decisions in aided vision system design. This paper describes four models; stereopsis, modulation transfer function area for stereopsis, probability summation and binocular summation, that may be useful in assessing the advantage of binocularity in aided vision.

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Assessing Binocular Advantage in Aided Vision

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Abstract

Advances in microsensors, microprocessors and microdisplays are creating new opportunities for improving vision in degraded environments through the use of head-mounted displays. Initially, the cutting-edge technology used in these new displays will be expensive. Inevitably the cost of providing the additional sensor and processing required to support binocularity brings the value of binocularity into question. Several assessments comparing binocular, biocular and monocular head-mounted displays for aided vision have concluded that the additional performance, if any, provided by binocular head-mounted displays does not justify the cost. The selection of a biocular display for use in the F-35 is a current example of this recurring decision process. It is possible that the human binocularity advantage doesn't carry over to the aided vision application, but more likely the experimental approaches used in the past have been too coarse to measure its subtle but important benefits. Evaluating the value of binocularity in aided vision applications requires an understanding of the characteristics of both human vision and head-mounted displays. With this understanding, the value of binocularity in aided vision can be estimated and experimental evidence can be collected to confirm or reject the presumed binocular advantage, enabling improved decisions in aided vision system design. This paper describes four computational approaches; geometry of stereopsis, modulation transfer function area for stereopsis, probability summation and binocular summation, that may be useful in quantifying the advantage of binocularity in aided vision.

Key Words: Head Mounted Display, Night Vision Goggle, Stereopsis, Modulation Transfer Function, Probability Summation

Introduction

Human vision, taken in its entirety, is an unparalleled sensing system but there are degraded environments (low light, rain, fog, smoke) where vision can be greatly improved or aided through an intermediary electronic sensor/display system. For the purpose of this paper an aided vision system is defined as a head-mounted display (HMD) that produces a spatially and temporally aligned image of the operator's environment. The resulting veridical perception allows the operator to navigate and manipulate the environment in a natural and efficient manner. Night vision goggles (NVGs), where the optical axes of a unity magnification inline sensor/display system is aligned with the operator's visual axes are an extremely successful example of an aided vision system for low light environments.

In the design of HMDs for aided vision, the decision to pursue a binocular, biocular or monocular system is based on a multitude of factors. Some of these factors such as weight, size, power and cost are quantifiable and reasonably well understood. Other important factors, such as the various parameters of visual performance, are more subtle, situationally dependent and less well-defined. Numerous studies comparing visual performance while using HMDs of different ocular configurations have produced inconsistent results (13,25,38). Extrapolation from these studies to predict visual performance using new HMD systems, or older systems in new environments, should be done with caution and in the context of known display and human visual characteristics.

The human visual sense is derived from an extremely complex neural process. Knowledge of this complex process is derived from a limited number of experiments conducted under a limited number of conditions. The accumulated knowledge is captured in simplified models. Models derived from one set of conditions can provide insight into other conditions, but adjustments to the models are often needed. Using this strategy, unaided vision models can serve as initial estimates of aided vision performance and point toward research processes that can extend current models to better predict performance using new aided vision systems.

In human vision the retinal image is processed in multiple neural streams. Analyzing the outcome of a single stream does not provide a comprehensive assessment of visual performance. In binocular vision the independent image information gathered by the two eyes are simultaneously compared, to extract stereoscopic depth information, and summed to improve image perception (21). An assessment of the value of binocularity under a given set of conditions needs to take both summation and comparison streams into consideration. It is important to note that the value of these two streams may be negatively correlated. For example, under low light conditions the summation stream's contribution may be extremely important in collecting sparse information from the scene while the comparative stream provides little benefit. Increasing the scene illuminance changes the relative contributions of the streams. In abundant light conditions the summation stream's contribution is reduced and the comparative stream's stereoscopic contribution is maximized. Spatial discrimination, a critical visual skill, is processed through both streams. There are three types of spatial discrimination discussed in this article, resolution, Vernier acuity, and stereoacuity. The first two, resolution and Vernier acuity, benefit from the summed inputs from the two eyes, while stereoacuity is dependent on a comparison of these inputs.

Resolution, the most familiar spatial discrimination, is the ability to distinguish the separation between two points (or lines) and is routinely measured in people using the Snellen eye chart. The resolution of optical equipment is measured using tri-bar and sine-wave charts. Vernier acuity and stereoacuity are less well-known, but make for an interesting comparison. They are both discriminations of misalignment. They both depend on the same initial physiology to include the focusing optics of the eye, the density of retinal photoreceptors, and the size of neuron receptive fields. In addition they can both be measured on the same experimental apparatus under nearly identical conditions; the only difference being the orientation of the perceived misalignment (4). The orientation determines whether the two eyes see nearly identical views that can be summed (Vernier acuity) or disparate views that must be compared (stereoacuity). This difference has measurable perceptual consequences. Under optimal viewing conditions Vernier and stereoacuity have very similar values, both as small as 2 arcsec (2,20), but as conditions degrade Vernier and stereoacuity values diverge with Vernier acuity being relatively resilient to the degradation (4).

Binocularity provides a definite performance improvement on several visual factors including visual field, depth perception, resolution, detection, and reaction time. Undoubtedly these improvements are important, but experimental evidence is required to confirm that the binocular advantage exists for any given application of a binocular aided vision system. Models are needed to guide this research, to aid in interpreting results, and to facilitate the accumulation of the acquired knowledge. Towards this goal, four potential models are discussed in this paper. Geometry of Stereopsis and the Modulation Transfer Function for Stereopsis models may be useful in defining the value of the comparative aspects of binocularity in aided vision systems. Probability summation and its progeny, binocular summation, may have predictive value regarding the summation aspects of binocularity in aided systems.

Geometry of Stereopsis

In the geometry of stereopsis model there are four main contributing factors to the stereo depth perception: 1) the distance between the observer's eyes, often called the interpupillary distance (P); 2) the distance from the eyes to the fixation point (D), also known as the vergence distance; 3) the distance between the fixation point and the object of interest, and 4) the spatial discrimination capabilities of the eyes. The first three factors define the geometric relationships between the relevant items to viewing condition. Cormack and Fox (12) provide a thorough discussion, including equations, of this geometry. The fourth factor defines the envelope of geometries that can be perceived by the binocular visual system. Stereoacuity (S) delineates the minimum perceptible depth difference (MPDD) boundary of the envelope, where:

$$MPDD=P/\{2[(P/2D)+\mathrm{Tan}(S/2)]\} - D$$

This boundary is graphically represented in Figure 1 for a variety of stereoacuities. The x-axis (abscissa) is fixation distance and the y-axis (ordinate) is the minimum distance a second object must be moved in from the fixation point for the observer to perceive that it is closer based on stereopsis. In this figure the 2 arc-seconds (arcsec) curve represents the predicted depth discrimination capabilities of an observer given excellent stereoacuity under optimal visual conditions. The additional curves show the predicted level of depth discrimination from a selection of reduced stereoacuity levels that could result from either a compromised visual system or degraded visual conditions. The geometry of stereopsis model predicts that stereo depth discrimination is best when viewing objects at near and that it gradually declines with increased viewing distance, with the rate of decline being heavily dependent on stereoacuity.

The introduction of a well-fit binocular NVG in front of the eyes changes the stereopsis viewing geometry little. The optical axes of the NVG tubes are coincident with the visual axes of the observer's eyes (i.e., the interpupillary distance is unchanged) and the unity magnification of the goggles leaves the viewing distance undistorted. In other words, the geometry of stereopsis model should apply to binocular night vision goggles and other similar aided vision devices. Theoretically, if the spatial relationships of a critical depth detection task were known, the model could be used to estimate the binocular HMD stereoacuity requirements for performing the task under aided vision conditions. Practically, the model has limited value without a method for determining the stereoacuity supported by a binocular HMD.

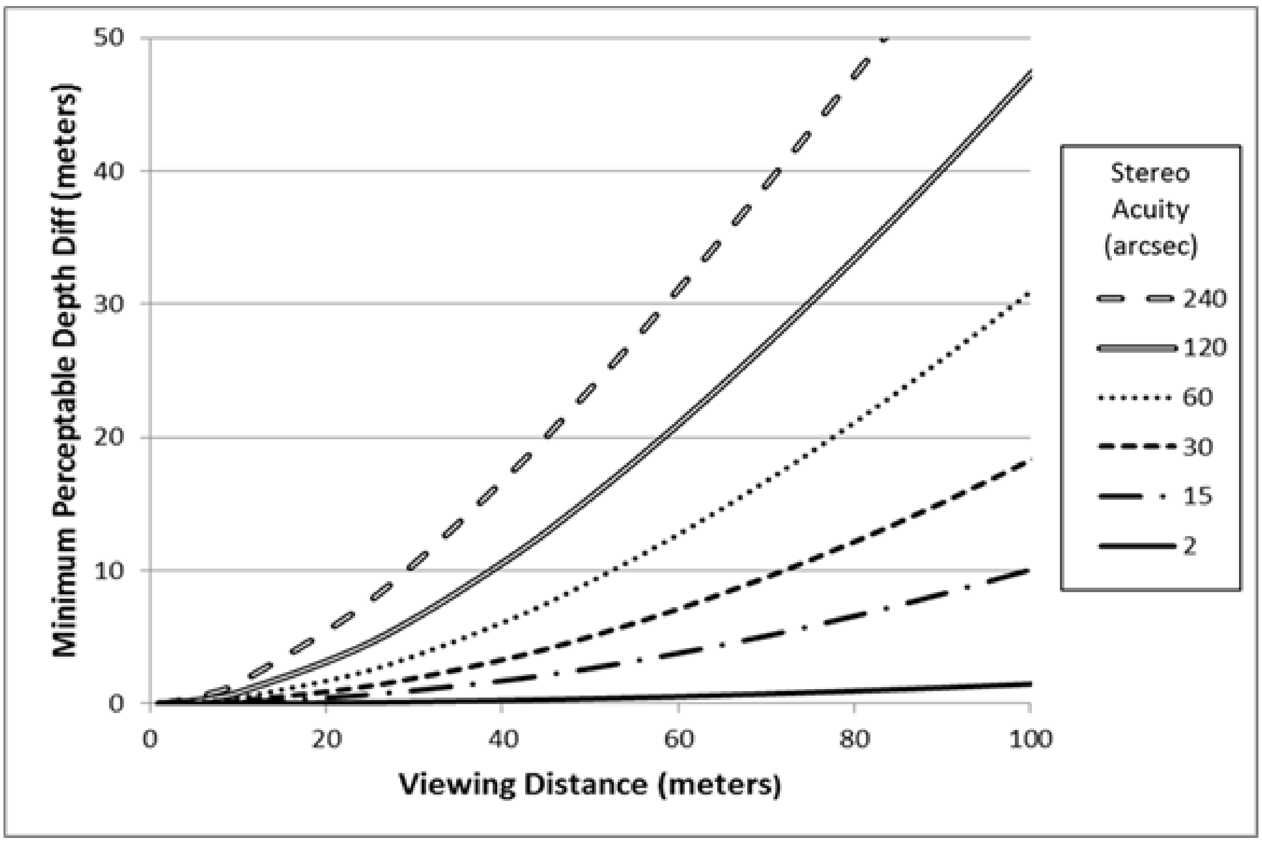

Figure 1. Minimum Perceptible Depth Difference (MPDD) by Viewing Distance for Several Stereoacuity Levels

Multiple investigations of NVGs using a Howard-Dolman apparatus have concluded that under good illumination, using high contrast targets, NVGs can support approximately 17 arcsec of stereoacuity (22). 17 arcsec is significantly less than the optimal stereoacuity for unaided vision, but Figure 1 suggests that it is sufficient to help with depth discriminations at short to moderate distances. Knight et al suspected that reduced resolution was the major contributor to this reduction in stereoacuity (22). Since resolution and stereoacuity are both spatial discriminations they should be highly correlated, but the relationship is complicated. Unaided stereoacuity is more vulnerable to degradations in image quality than either resolution or Vernier acuity. Stereoacuity has been shown to be more susceptible to reduced luminance (4,26), reduced view duration (47), defocus, spatial frequency filtering (46) and reduced contrast (16). Since it is impractical to measure every HMD's stereoacuity under every possible imaging condition, a predictive model of HMD stereoacuity performance is needed that takes these additional image quality factors into consideration. The model discussed next may help fulfill this need.

Modulation Transfer Function Area for Stereopsis

In many aided vision applications contrast is the primary limiting factor in the image. Laboratory evaluations of HMD resolution are often misleading as the intended operational environments do not typically contain the high levels of black on white contrast found in eye charts or test patterns. The reduced contrast of the earth tone colors found in natural scenes may be further reduced by camouflage or obscurants such as smoke, fog, rain or dust. Often it is reduced scene contrast that drives the desire to view the scene in a different spectral band and the need to use a HMD for a particular application.

Linear systems (i.e., Fourier) analyses, where an image is described as a series of sine wave components, has been extremely valuable in describing the relationship between spatial discrimination and contrast. It has been most widely used in the analysis of resolution in imaging systems, but is equally relevant to other spatial discriminations, including stereoacuity. The most common representation of linear systems based performance data for imaging is the modulation transfer function (MTF). In MTF measurements, a series of high contrast sine wave gratings with varying spatial frequencies are imaged through the optical system. For each grating frequency, the contrast in the resulting image is compared to the contrast in the original grating.

Every optical system suffers from imperfections including diffraction, reflections, aberrations, and scatter, which deviate light from its intended path and results in reduced image contrast. Poor optical systems disperse great amounts of light at large angles which causes substantial contrast loss for all grating frequencies, while good quality optical systems only suffer disproportionate amounts of contrast loss at higher frequencies. MTFs provide a graphical representation of measured contrast loss across a range of grating frequencies, and are typically graphed with spatial frequency on the abscissa and contrast on the ordinate, giving measured MTFs a characteristic appearance: the curve typically slopes down and to the right as it approaches the system's frequency cut-off, which defines the system's resolution. Figure 2 shows a traditional MTF representation, plotted on a log-log scaled graph, for a hypothetical HMD. The interpretation of the MTF curve is straightforward; contrast and spatial frequency combinations above and to the right of the curve cannot be produced by the optical system and are unavailable for image synthesis.

In optical systems designed for human viewing, the MTF is often graphed along with the human contrast threshold function (HCTF) for grating detection. The HCTF is defined as the minimum amount of contrast needed for a typical person to perceive each grating frequency. The HCTF is relatively flat for low spatial frequencies, but as grating frequency increases, approaching the visual system's frequency limit, more contrast is required to support perception. The absolute limit or resolution is reached when the function approaches a Michelson contrast of 1, a grating of dense black stripes on intense white background. Interpretation of the HCTF is clear; contrast and spatial frequencies below and to the right of the curve cannot be seen through the system. As portrayed in Figure 2, most HMD systems cannot produce the visual system's cut-off frequency; the HMD's MTF starts to fall earlier and crosses the HCTF at a lower frequency.

This intersection of the curves establishes the cut-off limit for a human using the HMD. The combined Human & HMD cut-off frequency is analogous to visual resolution discussed previously. Resolution, as a measure of an optical system's ability to image high frequencies, is a simple and useful tool but it is not a thorough description of image quality. Alternatively, MTFs provide a comprehensive description of optical performance across all spatial frequencies, but is cumbersome in practical application. A third approach, taking the area under the MTF, attempts to split the difference between the simple and comprehensive extremes with some success. The area under the MTF curve provides a single number that correlates with image quality, but lacks the intuitive interpretability that a familiar measure like resolution provides. Another limitation of MTF analysis is the assumption that all frequency and contrast combinations are equally valuable; obviously incorrect given the variable sensitivity of the human visual system. In this case subtracting the area under the HCTF from the MTF area insures that the most usable frequencies are given more weight in the measurement. This improved measure is known as the Modulation Transfer Function Area (MTFA) (3).

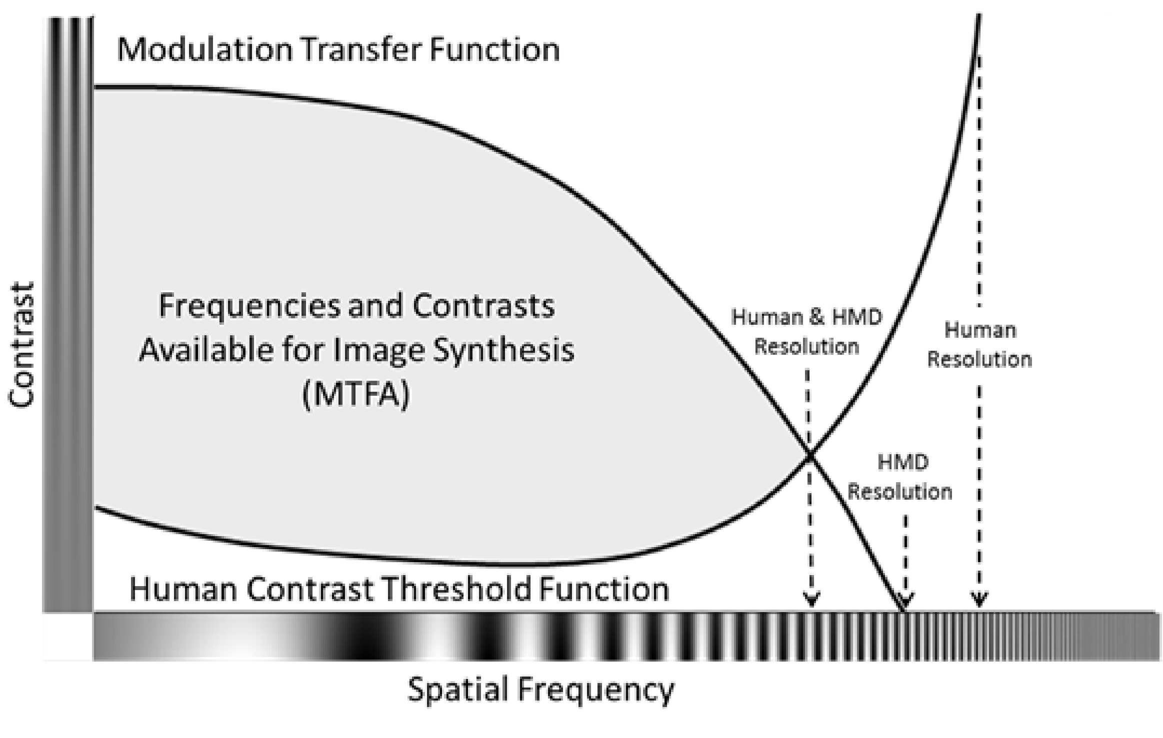

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Figure 2. Hypothetical Linear Systems Analysis for an Aided Vision HMD System

One last feature of linear systems analysis, the ability to cascade MTFs, makes it a particularly powerful modeling tool. Cascading MTFs is the process of calculating an overall system MTF by taking the product of the component MTFs. For example, the resolution of a myopic observer viewing a target through a NVG can be estimated by taking the product of the MTFs for the target, atmosphere, NVG and the observer's spectacle lens. This cascaded MTF could then be analyzed with the HCTF; the intersection of the two curves provides a resolution estimate for the particular viewing condition. In addition, the area between the cascaded MTF and HCTF defines the MTFA for the situation, providing a more general measure of the expected image quality.

Up to this point in the discussion, linear systems analysis and the consideration of human vision has assumed a single 2D sine wave image viewed by both eyes, but the techniques are equally valid for analyzing stereo image pairs. The principles of Fourier synthesis and analysis remain and the concepts of contrast, spatial frequency, cascading MTFs, and HCTF translate directly to stereo systems with two minor complications. First, the contrast required to detect subtle spatial differences in a stereo image pair is higher than the contrast required to detect a simple 2D grating; consequently a linear systems model for stereopsis requires an adjustment to the HCTF. Second, unlike resolution, the relationship between cut-off frequency and stereoacuity is unclear and needs to be explored.

HCTF is often described as a single function relating threshold visual detection to grating contrast and spatial frequency. It is more appropriate to think of HCTF as a series of functions dependent on many variables including grating parameters (luminance, duration of presentation, chromatic content, orientation, motion), observer characteristics (age, health, pupil size, adaptive state), and task requirements (detection, discrimination, identification). A huge number of psychophysical experiments have been conducted to explore these variables and their impact on the HCTF. Stereoscopic tasks have been used in many of these experiments. The models describing the relationship between contrast, spatial frequency and stereoacuity derived from these investigations can be complex. Here, for simplicity's sake, it is sufficient to focus on one of the early experiments conducted by Frisby and Mayhew (16). They used random dot stereograms to directly compare the contrast required to detect dots constructed from a narrow band of frequencies and the contrast required to perceive stereo depth encoded in the same dots. They found that for a large range of stereo disparities the stereo HCTF had the same shape as the simple detection HCTF but that approximately twice as much contrast was required to support the perception of stereoscopic depth. This new piece of information can be used to build a MTFA model for stereopsis.

In Figure 3, four curves are plotted together. The graph is similar to Figure 2, only the axes are linearly scaled to improve legibility. The first curve, NVG MTF, is the measured MTF of a generation 3 night vision goggle (17). The second curve, NVG & Target MTF, is the cascaded MTF of the NVG and a generic target. It is common in target detection modeling to assume uniform contrast across all target spatial frequencies (43). For this chart, target contrast is assumed to be .25, a typical value for a natural target and background. The third curve is a recommended HCTF for an adaptive luminance of 1.0 cd/m2 (3), well within a NVG's output range. The fourth curve, Stereo HCTF, is an estimate of the contrast threshold for supporting stereopsis calculated by doubling the HCTF value (consistent with the findings of Frisby and Mayhew). These four curves can be used to describe the spatial frequency bandwidth that is available to support both simple detection and stereoscopic tasks. In Figure 3, point (A) is both the predicted high frequency cut-off and resolution for a person using NVGs to detect a high contrast grating. Point (B) is the predicted high frequency cut-off for a person using NVGs to perceive depth in a high contrast stereo grating. Point (C) is the predicted high frequency cut-off and resolution for a person using NVGs to view a typical contrast target. Point (D) is the predicted high frequency cut-off for a person using NVGs to perceive stereoscopic depth in a typical contrast target. Line (E) is the low frequency cut-off as determined by target size and viewing distance. Moving nearer to the target enlarges its angular extent, expanding the low spatial frequencies in the target and increasing the bandwidth available for imaging. Conversely, moving farther way from the target reduces bandwidth available for imaging. The striped area (F) is the MTFA for stereopsis or the palette of spatial frequencies and contrasts that are available for stereo image synthesis. This figure shows how reducing the contrast of a target or increasing the viewing distance can reduce the available spatial bandwidth for supporting stereopsis. It clearly illustrates how an NVG can perform well on laboratory resolution measurements yet fail to support stereopsis in the operational environment due to limited contrast. Finally, this approach also defines two new variables, stereopsis cut-off frequency and stereopsis MTFA, which can be used in developing models for predicting stereoacuity for binocular HMDs.

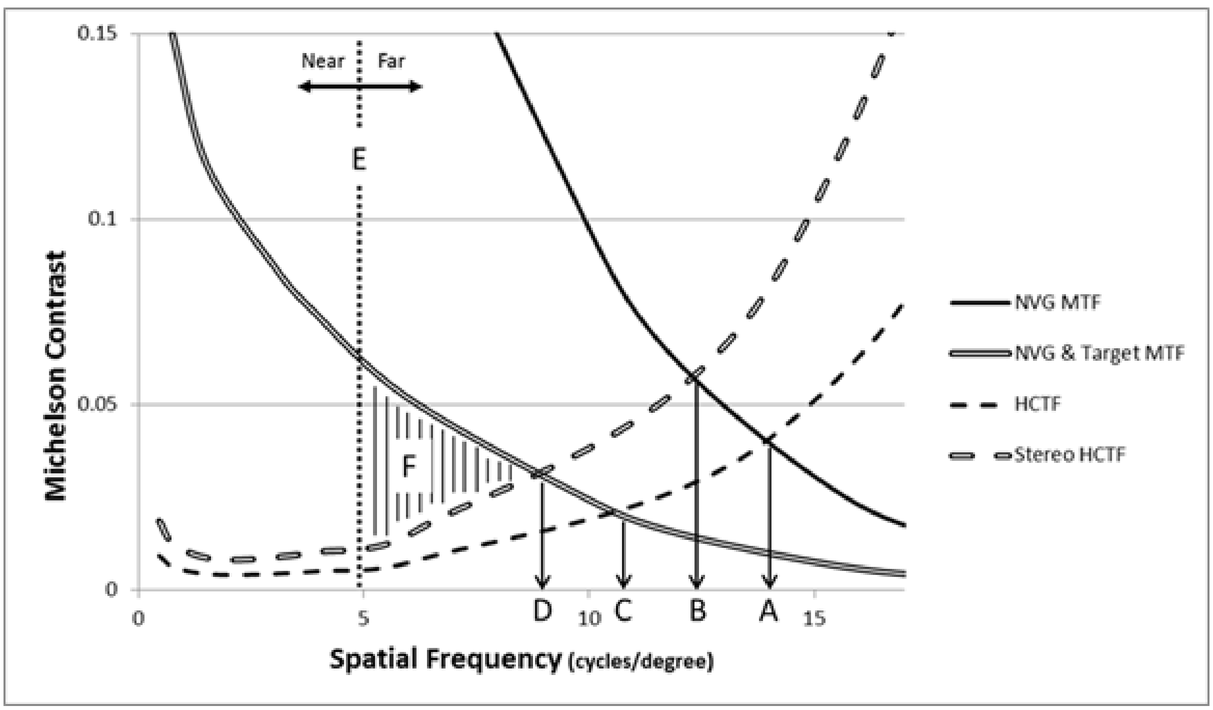

Figure 3. Linear Systems Analysis of High Contrast Grating and Low Contrast Target Viewed with NVGs (See Text for Explanation)

For example, one simple model assumes that stereoacuity maintains a constant proportional relationship to the period of the stereoscopic cut-off frequency. This proportion could (and arguably should) be expressed as a simple ratio; although this would obscure the abundance of evidence available to support the model. In the linear systems context a portion of a sine-wave's period is reported as a phase angle (complete linear systems analysis includes frequency, amplitude and phase analysis). Despite the computational inconvenience, the ratio-to-phase angle conversion is advantageous from both an imaging and physiological perspective (33). In stereo imaging, the left and right eye images contain the same objects; therefore the Fourier analysis of the two images will be nearly identical in terms of spatial frequencies and amplitudes. The binocular disparities that drive the perception of depth for objects in the scene are a result of local phase shifts between the two images. The local phase shifts are detected by visual cortex cells that are tuned to phase shifts between binocular retinal images. The existence of these phase sensitive cortical cells has been verified through direct cell recordings (1,39).

Psychophysical experiments describe the perceptual consequences resulting from the phase sensitive cells and indeed these experiments confirm a constant phase relationship between stereoacuity and cut-off frequency, for low to moderate spatial frequencies (8,32). Legge and Gu (23) generated spatial frequency versus stereoacuity curves for several observers and found phase angles ranging between 3 and 14 degrees. Taking the most conservative phase angle from this range and the cut-off frequency from Figure 3 (8 cycles/degree) we can estimate a stereoacuity for a person using Gen 3 NVG and looking at a .25 contrast target to be approximately 18 arcsec. This stereoacuity estimate can then be used in the geometry of stereopsis model to estimate the minimum perceptible depth for a given viewing distance that can be attributed to binocularity.

The linear systems analysis above assumes that the images presented to each eye are identical except for the small phase shifts resulting from their separate viewing locations. Asymmetries between the right and left eye's image in size, resolution, focus, contrast, and luminance distort the phase shifts and reduce stereopsis (10,27,41). If stereopsis is a priority, considerable diligence is required in the design, development, evaluation and manufacturing of binocular HMDs to ensure that the right and left channels are well-matched within the tolerances of the human visual system.

In summary, for binocular HMDs the maximal benefit from stereo is at near and the rate at which the benefit is lost with increasing viewing distance depends largely on the HMD's image quality. As image quality improves, the usefulness of the stereoscopic cues in binocular HMDs will increase, especially for moderate to long distances. Eventually binocular HMDs will support high-quality stereopsis at relevant distances for both helicopter and fixed-wing aircraft operations to include taxi, take-off, landing, terrain following, and formation flying.

Probability Summation

Probability Summation of Independent Detectors is a simplified model that has been used widely in multichannel sensory research (28,36,42). For binocular vision the model assumes that each eye acts as an independent detector and that the component processes building towards the response are stochastic. Given these assumptions, the model predicts for a variable input (stimulus) the required minimum (threshold) value to initiate a correct dichotomous output (response) will vary over time and that if the threshold is measured a large number of times, the distribution of the threshold values will be normal. This model has been used for many types of stimuli (spots, gratings, random-dot patterns) varied on a wide range of characteristics (size, luminance, contrast, duration, wavelength). Likewise many types of behavior can be used as the measured response, for example detection, resolution, identification, and comprehension. Normal distributions are most commonly graphed as bell-shaped functions, but an equally valid representation is the S-shaped cumulative function. In this case the cumulative function indicates the probability that the threshold is a given value or less. The cumulative function of threshold data is used regularly in psychophysical research where it is referred to as the Psychometric Function. In vision research it is also called the Frequency-of-Seeing or Probability-of-Seeing Curve. Figure 4 shows a hypothetical Probability-of-Seeing Curve for a standard normal threshold distribution for one eye and also the probability summation model for the two eyes. The model is straightforward. The two-eye probability of seeing curve is the sum of the individual eye probabilities minus the probability that both eyes see the stimulus:

$$P(\mathrm{cum}) = P(\mathrm{Eye}_1) + P(\mathrm{Eye}_2) - [P(\mathrm{Eye}_1) \text{ X } P(\mathrm{Eye}_2)]$$

The probability associated with seeing the stimulus with both eyes $[P(\mathrm{Eye}_1) \text{ X } P(\mathrm{Eye}_2)]$ is included in both $P(\mathrm{Eye}_1)$ and $P(\mathrm{Eye}_2)$ and therefore gets double counted, which is why it needs to be subtracted once in the calculation. If the two eyes are very similar the equation simplifies to:

$$P(\mathrm{cum}) = 2P(\text{single eye})-P(\text{single eye})^2$$

Several interesting points can be seen in Figure 4. If a stimulus is strong or suprathreshold, for instance 2.5 or more standard deviations above the mean threshold value, the stimulus would almost certainly be seen by either eye. Stimuli that are weak or subthreshold have very little chance of being seen with either eye. Consequently, the probability summation model predicts that probability of seeing experiments run at either suprathreshold or subthreshold levels of intensity have little chance of discriminating between the binocular and monocular conditions. If, however, the stimulus is near threshold, two independent eyes have a substantially better probability of seeing the stimulus compared to a single eye. The binocular benefit peaks with a .25 probability improvement at the mean threshold value. (Figure 4) Analyzing the benefit of binocularity at suprathreshold levels requires a different strategy, for example, one that involves the measurement of reaction time.

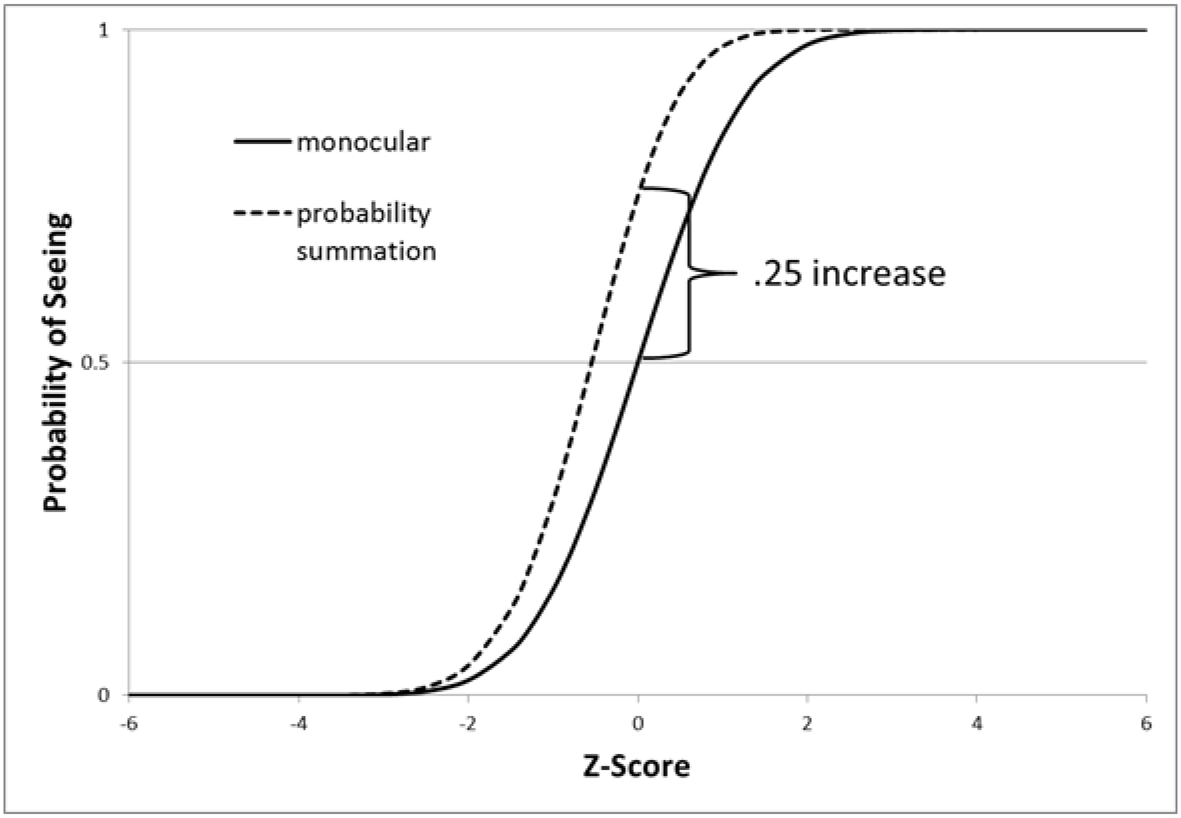

Figure 4. Probability-of-Seeing Curves Showing Predicted Improvement from Probability Summation due to Binocularity

The probability summation model can be applied to reaction times based on the previous assumptions, specifically two independent channels built from stochastic components. Called the race model, it assumes that the stimulus input races through the separate sensory channels with the fastest channel initiating the response (11,29,37). In the race model, the nature of the experimental variables are reversed, with the stimulus being dichotomous and the dependent measure of reaction time being continuous, thus allowing the race model to be used across the full spectrum of suprathreshold stimuli. The probability summation model has been extremely useful in guiding research in terms of experimental design and interpretation of results. Subsequently, several decades of research has shown that the probability summation model provides a conservative estimate of the performance enhancement derived from binocular vision. For the majority of people with normal binocular vision, probability summation underestimates visual performance because the two eyes work together, synergistically, better than predicted by their individual contributions.

Binocular Summation

In its most generic use, binocular summation simply means that sensory information from the left and right eyes are combined, resulting in an improved visual perception. Evidence for binocular summation exists when visual performance exceeds the predictions of probability

summation (5). Binocular vision performance improvements are most evident under luminance or contrast threshold conditions where the probability-of-seeing curves for binocular detection, resolution and Vernier acuity clearly exceed both measured monocular visual performance and the predicted binocular performance from probability summation (2,5).
In addition to the generic usage, binocular summation is also described as a specific model based on signals processing theory (SPT). This model assumes that the visual signals received and processed by the left and right eye channels are similar, highly correlated, and are summed together before a perceptual determination is made. Therefore, the resulting binocular signal (S_b) is simply the sum of two essentially identical monocular signals (S_m). Alternatively, the noise produced in the left and right eye channels is assumed to be similar in magnitude, stochastic and uncorrelated between the two channels. According to SPT, two uncorrelated noise sources are expected to sum as the root-sum-of-squares (9). Given these assumptions both left and right channel noise can be denoted as monocular noise (N_m) and an equation for predicting the improvement in signal-to-noise ratio for the binocular condition can be written as:

$$\frac{S_b}{N_b} = \frac{S_m + S_m}{\sqrt{N_m^2 + N_m^2}} = \frac{2S_m}{\sqrt{2} \times N_m} = \sqrt{2} \times \frac{S_m}{N_m}$$

This model is consistent with retinal physiology where detection thresholds are heavily influenced by dark noise in the retinal photoreceptors (19). Similar to probability summation, the predictions from the SPT binocular summation model can be graphed on a probability-of-seeing curve. The binocular summation curve is equivalent to the monocular curve shifted by a factor ($1/\sqrt{2}$) to the left. The relationship between the probability summation prediction and the binocular summation prediction depends on the slope of the monocular curve; the steeper the curve, the larger the separation between the binocular summation and the probability summation predictions.

Human contrast sensitivity measurement provides an obvious approach for verifying the SPT binocular summation model. The task of identifying a luminance increment over a background is conceptually equivalent to recognition of a signal over noise, and several researchers have demonstrated a consistent $\sqrt{2}$ relationship between monocular and binocular performance using this experimental paradigm (7,9). Figure 5 shows the results from one subject, on a contrast detection experiment conducted by Legge, replotted on a probability-of-seeing chart along with the probability summation and binocular summation predictions (24). Several interesting observations can be made from this figure. The binocular summation curve and the monocular curve turn up at similar locations but the ascent for the binocular summation curve is more rapid, resulting in a steeper slope and a clear separation between the two models' predictions near threshold. The measured binocular performance and the two models' predictions converge on a probability of one long before the measured monocular performance asymptotes. Most importantly, the subject's measured binocular performance exceeds both models' predictions at lower contrasts but comes into alignment with the binocular summation curve as contrast increases.

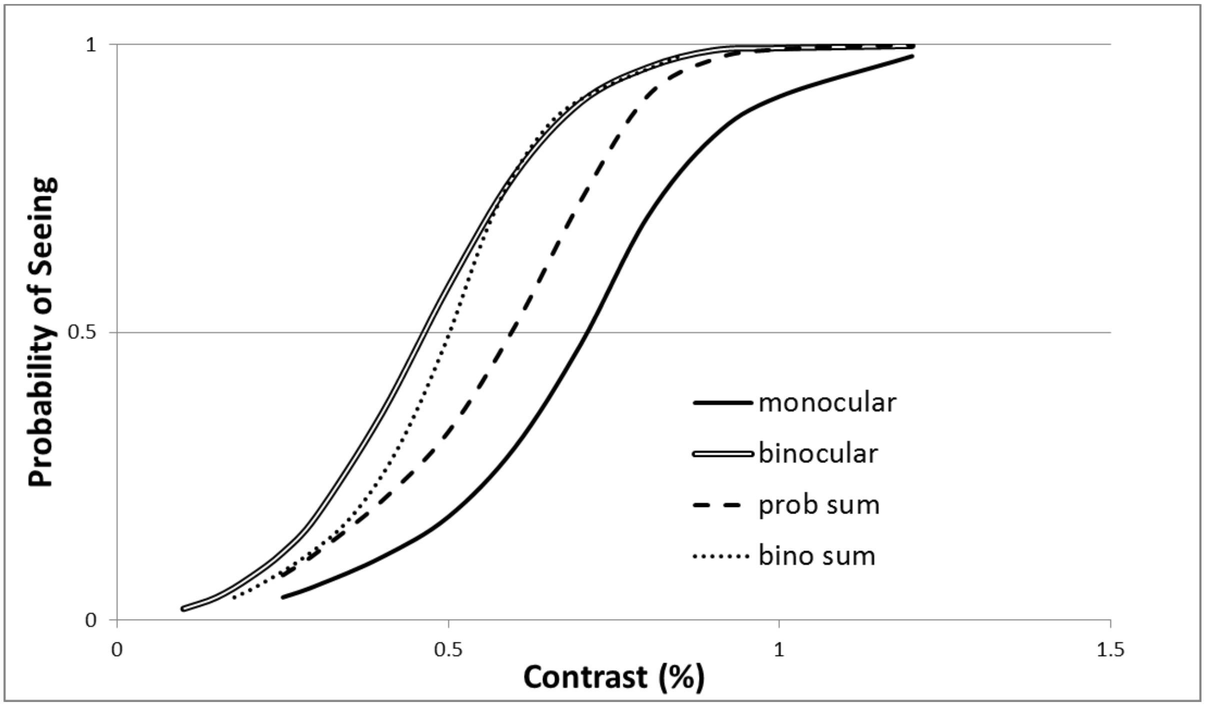

Figure 5. Measured Monocular and Binocular Probability-of-Seeing Curves (solid lines) Plotted with Probability Summation and Binocular Summation Model Predictions (dashed/dotted lines)

Demonstrating binocular summation at suprathreshold stimulus levels has largely depended on reaction time experiments with binocular summation being shown if reaction times are better than the race model prediction. Given the increased signal strength predicted by binocular summation and the well-known positive relationship between stimulus strength and neural processing speed, it is not surprising that binocular summation has been reliably demonstrated using this approach (7). The effect is robust over a large range of stimulus variables including, size, eccentricity, spatial frequency, contrast, and blur. The improvements in simple reaction time (button push or button release) cluster around 30 milliseconds in these experiments (7,30,44). The percent improvement on reaction time varies by experiment, but a 10% reduction in reaction time is common (6,7). The increased speed in the early stages of visual processing can also be measured electro-diagnostically using visual evoked potentials. A study of defocus effects on visual processing showed a 2-8 millisecond binocular facilitation at the level of the primary visual cortex, with the 8 millisecond binocular advantage occurring under the most degraded viewing condition (40). This example of increasing binocular facilitation under degraded conditions is not unique; similar findings have been found in experiments that use size, luminance, contrast, severity of distractors, and degree of eccentricity as independent variables (30,44,45).

The SPT model enables a theoretical comparison of the monocular, biocular, and binocular HMD conditions. Aided vision is a two-layered sensing system. The first system is the electronic HMD system. The second is the physiological (eye/brain) system. The SPT binocular summation model predicts that a binocular HMD will mitigate noise in both the electronic and physiologic sensing layers. The biocular HMD configuration only mitigates noise in the physiologic sensing layer, and the monocular HMD provides no noise mitigation in either layer. Night vision goggles are often used under near-threshold viewing conditions. The sensors in these devices are limited by a number of noise sources including dark current, thermal noise, and optical scatter, which are largely uncorrelated between the left and right channels of a binocular device. Given these sensor characteristics, binocular summation predicts a measurable improvement in performance for the binocular NVG configuration at threshold levels. Very little experimental evidence has been collected to confirm or refute this prediction. Significant resources are required to conduct rigorous NVG performance measurements including; light sources that reproduce the spectral radiance of the night sky, low light level photometers, a reliable psychophysical method, well-practiced observers, and the time to take a large number of measurements (34,35). Additionally, binocular summation, like stereopsis, depends on similar images being provided to the left and right eyes. Unfortunately, the complicated sensor, display, and optical designs required for binocular HMDs make building nearly identical displays for the two eyes difficult. If the inevitable differences between the two image channels exceed human visual tolerances, the advantages of binocularity are lost.

Discussion

Recent advances in microsensors, microdisplays, and microprocessors are creating new technology options for aided vision HMDs. The ability to see in previously inaccessible parts of the electromagnetic spectrum, along with the ability to overlay supplemental information, will create innumerable opportunities for successfully navigating difficult visual environments. As new HMD systems are developed the cost, power, and weight of providing a second sensor will have to be balanced against the expected benefits of binocularity.
Heretofore, the value of binocularity in aided vision has been controversial with much attention being given to a 1989 study by Wiley (48) comparing the stereoacuity obtained with binocular, biocular, and monocular NVGs which failed to demonstrate a clear performance advantage for the binocular configuration. This study has been used to support the conclusion that binocular HMDs have very limited value (38). Close examination of Wiley's study reveals that this conclusion may be premature. Considering the small number of measurements, the strict *p*-value and the use of now antiquated night vision devices, Wiley's study should not be considered a definitive declaration regarding the value of the binocular HMD configuration. A subsequent evaluation by Knight et al, using Gen 3 NVG's, concluded that binocular NVGs do support stereopsis, but at a reduced stereoacuity level (22). Additional experimental work is needed. A significant obstacle to accomplishing this research is the difficulty in building a comparable set of monocular, biocular, and binocular HMDs, where the binocular aspects of performance are not confounded by other variables such as luminance, magnification, or resolution. But as HMD technologies improve the desire and opportunity to assess the value of binocularity in aided vision systems will increase.

Experimental evidence is starting to demonstrate the value of binocularity in aided vision, at least for the limited visual range used in walking. Binocularity has been shown to improve walking speed over an obstacle course by 10% relative to the monocular condition (18). The Army Research lab conducted an analogous walking experiment utilizing binocular, biocular, and monocular, Gen 3 NVGs and found a very similar advantage for the binocular condition (14,15). Another notable experiment estimated target detection ranges for binocular and monocular NVGs. Resolution measurements were obtained under well-controlled conditions using several levels of ambient illumination. The results of the measurements were then used along with the Johnson Criteria to create detection models for military-relevant targets. The model for a human target under 1/4 moon illumination estimated a detection range of 372 meters for the binocular night vision goggle condition, versus 340 meters for the monocular goggle (31). Given the effective range of individual weapons, the 32 meter (approx. 10%) improvement in detection distance could be critically important.

Conclusion

In theory, the unaided binocular vision benefit should transfer to the aided vision, HMD environment. Binocularity in human vision provides performance benefits across a wide spectrum of human behavior. This behavior is a result of at least two parallel neural streams: A comparative stream that extracts depth information from the binocular image, and a summation stream that combines the image information resulting in improved perception. A comprehensive assessment of the advantages of binocularity has to take both streams into consideration. A thorough assessment of binocularity is complicated by large variability in human performance. Consequently, well-designed and rigorously executed experiments are necessary to reliably measure the benefits of binocularity. Models, specifically the geometry of stereopsis, linear systems analysis, probability summation, and binocular summation models of vision, have been extremely helpful in designing the experiments that ultimately demonstrated the performance advantages provided by binocular vision.

These models should likewise be useful for predicting aided vision performance and for designing experiments to validate those predictions. A basic prediction from the geometry of stereopsis and MTFA models is that improvements in image quality will increase the viewing distances over which binocularity contributes to depth perception. The probability and binocular summation models predict substantial improvements in visual performance under near-threshold viewing conditions. They also predict that reaction times for suprathreshold tasks should be slightly improved for binocular HMDs. Whether these expected binocular HMD benefits are meaningful depends on the specific aided vision application.

References

1. Anzai A, Ohzawa I, Freeman R. Neural mechanisms for encoding binocular disparity: receptive field position versus phase. J Neurophysiol 1999 Aug; 82(2):874-90.
2. Banton T, Levi D. Binocular summation in Vernier acuity, J Opt Soc Am A. 1991 Apr; 8(4):673-80
3. Beaton R, Farely W. Comparative study of the MTFA, ICS, and SQRI image quality metrics for visual display systems Wright-Patterson Air Force Base OH: Armstrong Laboratory; 1991 Sep. Report No: AL-TR-1992-0001. DTIC Accession No: ADA252116
4. Berry R, Riggs L, Duncan C. The relation of Vernier and depth discriminations to field brightness. J Exp Psychol 1950 Jun; 40(3):349-54.
5. Blake R, Fox R. The psychophysical inquiry into binocular summation. Percept Psychophys 1973; 14(1):161-185
6. Blake R, Martens W, Di Gianfillipo A. Reaction time as a measure of binocular interaction in human vision. Invest Ophthalmol Vis Sci 1980 Aug; 19(8):930-41
7. Blake R, Sloane M, Fox R. Further developments in binocular summation. Percept Psychophys 1981; 30 (3):266-276
8. Bradley A, Skottun B. Effects of contrast and spatial frequency on Vernier acuity. Vision Res. 1987; 27:1817-24
9. Campbell F, Green D. Monocular versus binocular visual acuity. Nature 1965 Oct 9; 208(5006):191-2
10. Chang Y, Lee J, Kim N, Lee D, Chang J, Han S. The effects of interocular differences in retinal illuminance on vision and binocularity. Graefes Arch Clin Exp Ophthalmol. 2006; 244:1083-1088
11. Colonius H, Diederich A. The race model inequality: interpreting a geometric measure of the amount of violation. Psychol Rev 2006 Jan; 113(1):148-54
12. Cormack R, Fox R. The computation of retinal disparity. Percept Psychophys 1985 Feb; 37(2):176-8.
13. Crowley J, Haworth L, Szoboszlay Z, Lee A. Helicopter pilot estimation of self-altitude in a degraded visual environment. Fort Rucker AL: U.S. Army Aeromedical Research Lab; 2000 Sep. Report No. USAARL 2000-03. DTIC Accession No: ADA385106
14. CuQlock-Knopp V, Sipes D, Torgerson W, Bender E, Merritt J. Human off-road mobility, preference, and target-detection performance with monocular, biocular, and binocular night vision goggles. Aberdeen Proving Ground MD. Army Research Laboratory; 1996 Aug. Report No: ARL-TR- 1170. DTIC Accession No: ADA314315
15. CuQlock-Knopp V, Sipes D, Torgerson W, Bender E, Merritt J. A comparison of monocular, biocular, and binocular night vision goggles for traversing off-road terrain on foot. Aberdeen Proving Ground MD. Army Research Laboratory; 1995 Mar. Report No: ARL-TR-747. DTIC Accession No: ADA294018
16. Frisby J, Mayhew J. Contrast sensitivity function for stereopsis. Perception 1978; 7:423-9
17. Fullenkamp S, Trissell T, Aleva D, Dixon S, Task H. Modulation transfer function as a predictor of visual acuity using a night vision device. In: Rash CE, Reese CE, eds.

Helmet- and Head-Mounted Displays X: Technologies and Applications. Proceedings of SPIE 2005; 5800:55-64
18. Hayhoe M, Gillam B, Chajka K, Vecellio E. The role of binocular vision in walking. Vis Neurosci 2009 Jan-Feb; 26(1):73-80
19. Holcman D, Korenbrot J. The limit of photoreceptor sensitivity: molecular mechanisms of dark noise in retinal cones. J Gen Physiol 2005 Jun; 125(6):641-60
20. Howard H. A test for the judgment of distance. Trans Am Ophthalmol Soc 1919; 17:195-235
21. Jones R, Lee D. Why two eyes are better than one: the two views of binocular vision. J Exp Psychol Hum Percept Perform 1981 Feb; 7(1):30-40
22. Knight K, Apsey D, Jackson W, Dennis R. A comparison of stereopsis with ANVIS and F494 night vision goggles. Air, Space and Environmental Medicine 1998 Feb; 69(2): 99-103
23. Legge G, Gu Y. Stereopsis and contrast. Vision Res. 1989; 29:989-1004
24. Legge G. Binocular contrast summation-1. Detection and Discrimination. Vision Research 1984; 24(4): 373-383
25. Lippert T. Fundamental monocular/binocular HMD human factors. In Lewandowski RJ, ed. Helmet-Mounted Displays II. Proceedings of SPIE; Orlando, FL. 1990; 1290:185-191
26. Livingstone M, Hubel D. Stereopsis and positional acuity under dark adaptation. Vision Res 1994 Mar; 34(6):799-802
27. Lovasik J, Szymkiw M. Effects of aniseikonia, anisometropia, accommodation, retinal illuminance, and pupil size on stereopsis. Invest Ophthalmol Vis Sci 1985 May; 26(5):741-50
28. Marks L, Veldhuizen M, Shepard T, Shavit A. Detecting gustatory–olfactory flavor mixtures: models of probability summation. Chem Senses. 2012 Mar; 37(3):263-77
29. Miller j, Ulrich R. Simple reaction time and statistical facilitation: a parallel grains model. Cogn Psychol 2003 Mar; 46(2):101-51
30. Minucci P, Connors M. Reaction time under three viewing conditions: binocular, dominant eye, and nondominant eye. J Exp Psychol. 1964 Mar;67:268-75
31. Monaco W, Weatherless R, Kalb J. Enhancement of visual target detection with night vision goggles. Aberdeen Proving Ground MD. Army Research Laboratory; 2006 Jun. Report No: DTIC Accession No: ADA448466
32. Morgan M, Watt R. Mechanisms of interpolation in human spatial vision. Nature 1982 Oct; 299(5883):553-5
33. Oppenheim A, Lim J. The importance of phase in signals. Proceedings of the IEEE 1981 May, 69(5): 529-541
34. Pinkus A, Task H. Measuring observers' visual acuity through night vision goggles. Proceedings of the 36th Annual Symposium Safe Association; 1998: 1-11
35. Pinkus A, Task H, Dixon S, Goodyear C. Reproducibility limits of night vision goggle visual acuity measurements. SAFE Journal 2000; 30(1):131-139
36. Pirenne M. Binocular and uniocular thresholds in vision. Nature 1943; 152:698-699
37. Raab D. (1962). Statistical facilitation of simple reaction times. Trans N Y Acad Sci 1962; 24:574–590

38. Rash C, McLean W, Mora J, Ledford M, Mozo B. Helmet-mounted displays: design issues of rotary–wing aircraft. Fort Rucker AL: U.S. Army Aeromedical Research Lab; 1998 Jul. Report No: USAARL 98-32. DTIC Accession No: ADA352464
39. Smith E, Chino Y, Ni J, Ridder W, Crawford M. Binocular spatial phase tuning characteristics of neurons in the macaque striate cortex. J Neurophysiol 1997 Jul; 78(1):351-65
40. Sotiris P, Dionysia P, Trisevgeni G, David A, Miltiadis K. Binocular summation improves performance to defocus-induced blur. Invest Ophthalmol Vis Sci 2011; 52:2784-9
41. Stevenson S, Cormack L. A contrast paradox in stereopsis, motion detection and vernier acuity. Vision Res 2000; 40:2881-4
42. Treisman M. Combining information: probability summation and probability averaging in detection and discrimination. Psychological Methods 1998 Jun; 3(2):252-265
43. Vollmerhausen R, Jacobs E, Driggers R. New metric for predicting target acquisition performance. Optical Engineering 2004; 43:2806-2818
44. Wakayama A, Matsumoto C, Ohmure K, Inase M, Shimomura Y. Influence of target size and eccentricity on binocular summation of reaction time in kinetic perimetry. Vision Res 2011 Jan; 51(1):174-8
45. Wakayama A, Matsumoto C, Ohmure K, Inase M, Shimomura Y. Influence of background complexity on visual sensitivity and binocular summation using patterns with and without noise. Invest Ophthalmol Vis Sci 2012 Jan; 53(1):387-93
46. Westheimer G, McKee S. Stereoscopic acuity with defocused and spatially filtered retinal images. J Opt Soc Am 1980; 70:772-778
47. Westheimer G, Pettet M. Contrast and duration of exposure differentially affect Vernier and stereoscopic acuity. Proc R Soc Lond B Biol Sci 1990; 241: 42-46
48. Wiley R. Visual acuity and stereopsis with night vision goggles. Fort Rucker AL: United States Army Aeromedical Research Laboratory; 1989 Jun. Report No. USAARL 89-4. DTIC Accession No: ADA211552