10 VISUAL PERCEPTION AND COGNITIVE PERFORMANCE

José E. Capó-Aponte
Leonard A. Temme
H. Lee Task
Alan R. Pinkus
Melvyn E. Kalich
Allan J. Pantle
Clarence E. Rash

The Warfighter in the modern battlespace has a predetermined, but ever-changing, set of tasks that must be performed. Performance on these tasks is affected strongly by the amount and quality of the visual input, as well as by the resultant visual perception and cognitive performance. Visual perception is defined as the mental organization and interpretation of the visual sensory information with the intent of attaining awareness and understanding of the local environment, e.g., objects and events. Cognition refers to the faculty for the human-like processing of this information and application of previously acquired knowledge (i.e., memory) to build understanding and initiate responses. Cognition involves attention, expectation, learning, memory, language, and problem solving.

The direct physical stimuli for visual perception are the emitted or reflected quanta of light energy from objects in the visual environment that enters the eyes. It is important to understand that the resulting perception of the stimuli is not only a result of their physical properties (e.g., wavelength, intensity, and hue) but also of the changes induced by the transduction, filtering, and transformation of the physical input by the entire human visual system.

This chapter explores some of the more important visual processes that contribute to visual perception and cognitive performance. These include brightness perception, size constancy, visual acuity (VA), contrast sensitivity, color discrimination, motion perception, depth perception and stereopsis. An analogous discussion of input via the auditory sense is discussed in Chapter 11, *Auditory Perception and Cognitive Performance*.

Brightness Perception

In physics, the luminance of an object is exactingly defined as the luminous flux per unit of projected area per unit solid angle leaving a surface at a given point and in a given direction. A more useable definition is the amount of visible light that that reaches the eye from an object. But, when an observer describes how “bright” an object appears, he/she is describing his/her brightness perception of the object. This brightness is the perceptual correlate to luminance and depends on both the light from the object <u>and</u> from the object’s background region.

Human visual perception of brightness and lightness involves both low-level and higher levels of processing that interact to determine the brightness and lightness of parts of a scene (Adelson, 1999).[1] If a scene was scanned by a photodetector, it would measure the amount of luminance energy at each point in the scene; the more light coming from a particular part of the scene the greater the measured value. The human eye’s retinal receptors (cones) respond in a similar manner when a scene is imaged unto it. However the appearance (perception) of a region of the scene can be drastically altered without affecting the response of retinal receptors. The well-known simultaneous contrast effect demonstrates this phenomenon (Figure 10-1). In reality, the two center regions have

---

[1] *Brightness* is the perceptual correlate of luminance and may be thought of as perceived luminance; *Lightness* is the perceptual correlate of reflectance and may be thought of as perceived reflectance.

the same luminance, but their apparent greyness' (luminance) are different and depend upon spatial interactions with the surround. The grey region surrounded by a dark area looks (is perceived) brighter than the same grey region surrounded by a light region. Hering (1878) attributed this effect to adaptation and local interactions. This phenomenon is just one example of a number of illusions that illustrate problems that can arise when one visual element is viewed in the context of others. While the human visual system is very good at such complex tasks as edge detection and compensation for ambient lighting conditions, it sometimes can alter the appearance of the stimulus in unexpected ways before its message reaches the conscious part of the brain (Flinn, 2000).

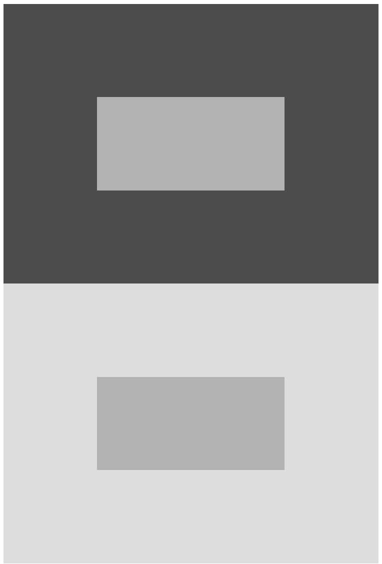


Figure 10-1. The simultaneous contrast effect.

The illusion associated with simultaneous contrast is not confined to grayshade images; it is equally applicable in the presence of color. Color perception has a strong dependency on two adjacent colors (Dahl, 2006). Figure 10-2 illustrates the different perception of the same blue color tone with two different backgrounds (Witt, 2007). While in Figure 10-2a blue is perceived as dark and opal, the same blue in Figure 10-2b is perceived as bright.

Two side-by-side colors interact with one another and change our perception according. Since colors rarely are encountered in isolation, simultaneous contrast will affect our perception of the color that we see. Consider a realistic example involving red and blue flowerbeds adjacent to one another in a garden; their perceived colors will be modified where they border each other. The blue will appear green, and the red will appear orange. The real colors are not altered; only our perception of them changes. Simultaneous contrast affects every pair of adjacent colors. This illusion is strongest when the two colors are complementary colors. Complementary colors are pairs of colors, diametrically opposite on a color circle (wheel) (Figure 10-3). Yellow complements purple; if yellow and purple lights are mixed, white light results. In the example of the red and blue flowerbeds, the red bed makes the blue bed seem green because it induces its complementary color, green, in the blue bed. The blue bed makes the red bed seem orange because it induces its complementary color, yellow, in the red bed.

When presenting information on helmet-mounted displays (HMDs) and other displays, this phenomenon of simultaneous contras is an important user interface design consideration The surroundings of a area of color will not only affect color brightness perception but also hue. This important property of adjacent colors should be considered in user interface designs and particularly where colors could be best used in structuring simple interfaces (Witt, 2007).

Figure 10-2. Simultaneous color contrast effect (adapted from Witt, 2007).

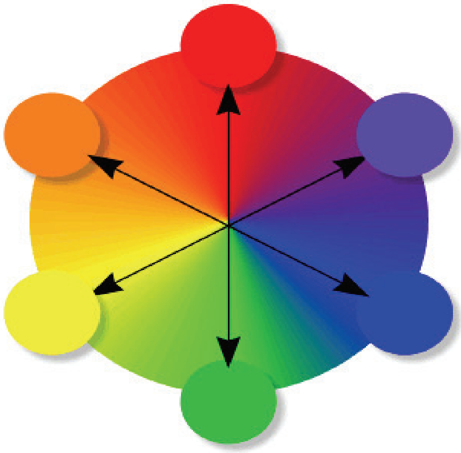


Figure 10-3. Complementary colors on color circle (wheel).

Size Constancy

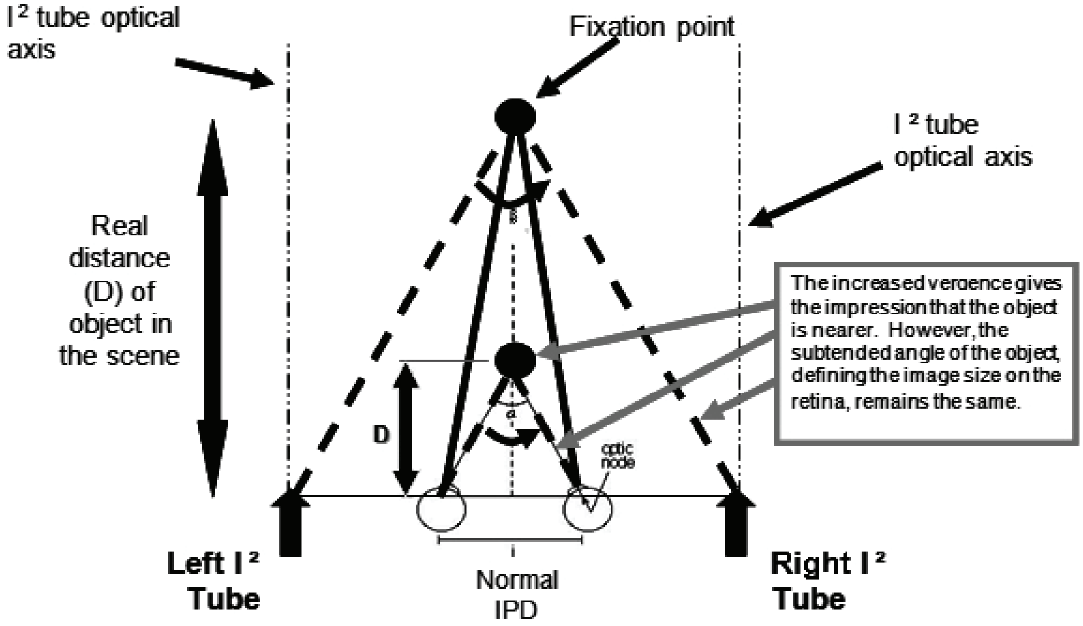
Size constancy is the recognition that the same object viewed at different distances and orientations is interpreted and can appear to be the same size and shape, regardless of image changes at the retina due to distance, visual angle and perspective. This is usually combined with the easy, routine human ability to respond to the object appropriately. Size constancy labels a large percentage of the perceptual and cognitive processes that provide a stable view of the world. It has been the subject of investigation since the ancient Greeks with many seminal papers that provide excellent discussions on the issues associated with perceptual constancy (e.g., Blake and Sekuler, 2005; Cutting and Vishton, 1995; Epstein, Park and Casey, 1961; Graham, 1966; Luo, 2007; Roscoe, 1984; Stevens, 1951; Wagner, 2006a, 2006b; Woodworth and Schlosberg, 1954; Zalevski, Meehan and Hughes, 2001). A consensus of these papers and their historical reviews is that "There is no such thing as an impression of size apart from an impression of distance" (Gibson, 1950).

There are very practical reasons for understanding how we reliably relate our representative perceptions to objective space when there is a less-than-"transparent" device like a HMD in-between. A prominent individual once asked what the value was of studying vision in aviation. The simple answer is, try flying without it. A more nuanced response is that we don't always see things as they are and we need to know how to deal with that. Humans survive because of our ability to figure out what is in the environment and respond in suitable ways.

As elegantly described by Cutting and Vishton (1995), we understand the layout of objects in space, their size and distance, by using multiple sources of information weighted in a hierarchical fashion that is based largely on information availability, task, and logarithm of distance. We actively work to assemble a functionally accurate representation of objective space and the layout of objects it contains.

Our ability to assemble the information sources necessary to provide a useful perceptual representation of layout under continuously changing conditions depends on redundancy to guard against failure of information sources and on the ability to correct errors (Cutting and Vishton, 1995). HMDs usually constrain or degrade this active assembly process (e.g., reducing field-of-view (FOV), reducing contrast, reducing resolution). These degradations have an impact on our ability to create an accurate picture of what is out there and where it's located, thereby allowing appropriate behavior (Zalevski, Meehan and Hughs, 2001). Redundancy allows flexibility and the ability to adapt to an amazing variety of situations by assembling reliable sets of information sources. Witness a pilot's ability to adapt when using the Integrated Helmet and Display Sighting System (IHADSS), a monocular display used on Apache helicopters. It displays visually degraded imagery and symbology with a narrow FOV that requires active suppression of the image in one eye to avoid binocular rivalry.

Hyperstereopsis provides another example of how HMDs can impact the perception of objects. It is created when image intensifier (I^2) tubes are mounted temporally on the sides of a helmet (with a separation distance greater than normal) and their images frontally displayed on a combiner. Figure 10-4 shows how such a design can paradoxically make an object appear closer and smaller. Normally when an object is closer it forms a larger image on the retina.



The increased vergence gives the impression that the object is nearer. However, the subtended angle of the object, defining the image size on the retina, remains the same.

Figure 10-4. Size constancy is affected by hyperstereopsis when image intensifier (I^2) sensors are mounted on the sides of a helmet. Due to the apparent increase in interpupillary distance, near objects can paradoxically appear closer and smaller.

Another consequence of hyperstereopsis is diagramed in Figure 10-5. The near ground appears to rise up to the observer, while the ground farther away looks normal. This is because retinal disparity and convergence are reduced when viewing objects a few meters out and absent for greater distances.

It should be noted that there is considerable evidence that the distortions of object in visual space begin to wane with experience, as a pilot adapts to the impact of hyperstereopsis (Kalich et al., 2007; Priot et al., 2006). A recent study evaluating pilot debriefings from 3 pilots wearing a hyperstereo-producing HMD seemed to confirm this impression (Kalich et al., 2009).

Figure 10-5. Increased separation of I^2 tubes mounted on a HMD exaggerates horizontal, but not vertical perspective. The increased horizontal perspective makes near objects appear closer, as represented by the grid lines, creating a 'crater' illusion. The distant ground appears to level off due to reduced effects of convergence and retinal disparity.

Zalevski, Meehan and Hughes (2001) reviewed the effect of using binocular NVGs on size estimates. NVGs use electro-optical image intensification to amplify visible light and near infrared energy. The images created are monochromatic and have less resolution and contrast than we are used to during the day, consequently reducing the use of retinal disparity as a source of distance information. In addition, the images have a 'softer' appearance, and there is a random scintillation produced by electronic noise. The FOV of most modern binocular NVGs is 40^o. Combined with the degraded image, this increases the potential for spatial disorientation.

In general, as ambient light declines and images from NVGs deteriorate, the estimate of object distance increasingly relies on the visual angle of objects (Zalevski, Meehan and Hughes, 2001). Depth perception diminishes. As size and shape constancy depend on the availability of depth information, the perception of size constancy diminishes. Size constancy works best in an environment rich with depth cues,

The concept of retinal image size, combined with distance, provides a basis for size constancy (Figure 10-6). Epstein, Park, and Casey (1961) point out that this relationship manifests itself in two distinct ways. First is "an object of known physical size uniquely determines the relation of the subtended visual angle to apparent distance." Second, often called Emmert's Law, is that "the apparent size of an object will be proportional to distance when retinal size is constant."

Note that the issue of distance is central to both of these statements. In the first case, if we don't know the distance, due to reduced visual information, as when using NVGs with very low ambient light (starlight and or clouded night), we have to use visual angle subtended by objects. A large object objectively some distance away may be judged as smaller, and a smaller, near object may be judged to be farther away than it actually is. This could make an estimate of closing velocity problematical. Emmert's law is particularly important when using see-through HMDs for near work like surgery. The information on the display forms an image on the retina that is of constant size. This can interact with surfaces seen through a display. As a surface appears closer, the displayed information can appear smaller; as the surface appears farther away the image can appear larger.

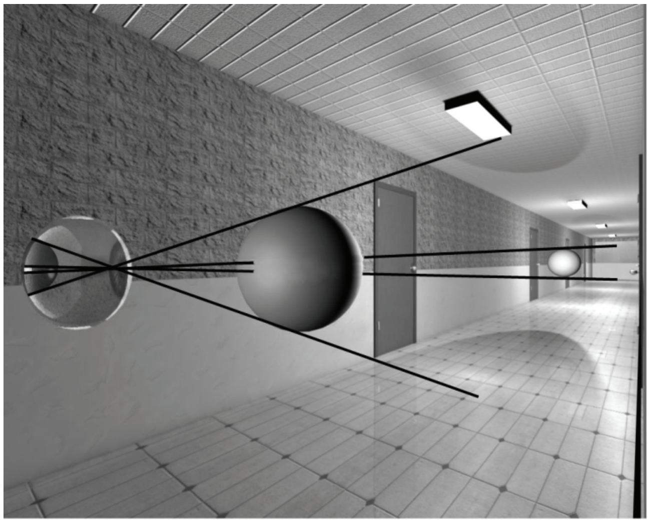


Figure 10-6. When an object, a sphere in this case, is viewed at different distances, the angle subtended at the eye, and correspondingly at the retina, is changed. Distant objects subtend a smaller visual angle and produce a smaller retinal image. Near objects subtend a larger angle and the retinal image appears larger.

Context also interacts with how we see and interact with objects. Context can make one distant object that subtends the same angle at the retina as another appear larger (Figure 10-7). By using movement and additional sources of information, we are usually able to arrive at a correct interpretation of the size of objects and their layout. However, when movement is restricted, as is the case with a pilot, it may be very difficult to obtain a correct interpretation of object size and distance.

Figure 10-7. A hallway rich with distance cues provides a context that makes the two identical black discs, ones that subtend the same visual angle, appear to be of different size. In most natural situation this can be corrected by changing position or using additional information, such as knowledge of their actual size.

Another aspect of size constancy is the use of information and memory (cognitive factors) to evaluate size (Blake and Sekuler, 2005). It is clear in Figure 10-8 that the people and cars that we identify that form a smaller angular subtense are behind the people who appear larger; and we behave accordingly. Environments rich in information sources provide many cognitive cues for distance and size. These are important for determining how we respond. Any contrivance placed between objective and representational visual spaces can reduce the number of sources of information about layout, decrease our ability to compensate for errors, and decrease chances for appropriate behavior as we try to navigate the real world.

Figure 10-8. Images of individuals and cars in this photograph that subtend smaller angles are normally treated as about the same size as the individuals and cars that are actually seen as larger. This is in large part due to our knowledge and memory. We also place the identified smaller object images in the background and the larger in the foreground, a depth interpretation. This ability to treat objects at different distances as the same actual size is critical when a pilot is on approach for landing.

Cutting and Vishton (1995) segment surrounding egocentric space into personal space (within 2 meters [m] [6 feet]), action space (within about 30 m [98 feet]), and vista space (beyond 30 m). The way we handle information, manipulate and deal with objects, the time frame of events, and the sources of motion differ in each of these egocentric regions In general, the order of relative dominance or efficacy of information about layout is occlusion, retinal disparity, relative size, convergence and accommodation for personal space; occlusion, height in the visual field, binocular disparity, motion perspective, and relative size for action space; and occlusion, height in the visual field, relative size, and aerial perspective for vista space. Each of these sources of information about layout can be divided into sources that are invariant with the logarithm of distance, sources that dissipate with the logarithm distance, and aerial perspective, increasing in effectiveness with logarithm of distance.

For example, occlusion, which is invariant with distance, almost always dominates, regardless of the egocentric region of operation. On the other hand, accommodation and convergence dissipate with distance and have little impact beyond personal space on assembling an accurate perception of layout. Similarly, the efficacy of retinal disparity, operating well into action space, also has reducing impact on how we assemble the sources of information to form a perception of the layout of perceptual space. A similar argument can be made regarding textural gradients. Even under conditions of hyperstereopsis, the impact of retinal disparity is significantly reduced beyond 30 m (98 feet) (Kalich et al, 2007).

The efficacy of ocular cues like convergence is significantly reduced beyond 6 m (20 ft), and beyond 30 m (98 ft). As ones' attention moves into action space and beyond, monocular sources of information such as interposition/occlusion, linear perspective, and motion parallax, increasingly dominate (Blake and Sekuler, 2005; Wagner, 2006a). In discussing this issue Zalevski, Meehan and Hughes (2001) state that motion parallax cues

> "…are most useful in visually complex environments such as open woodland and urban environments, and possibly less so over expanses of water or flat desert. Motion perspective, a cue resulting from the change in angular size of objects as they are approached (Braunstein, 1976), will be affected by the visibility and contrast of objects which, in the case of NVGs, is determined by illumination and reflectivity of objects. Another general source of spatial information is object familiarity, and cultural objects and structures such as vehicles and buildings on the ground can serve as "anchoring" cues for spatial perception, particularly object size."

Hermans (1937) very convincingly showed that convergence directly impacts the apparent size of objects. In general, objects requiring greater convergence appear smaller than the same objects viewed monocularly. As paired objects that are different distances from an observer, but angularly near to one another, move farther away, differences in their respective convergences are reduced. Consequently apparent size differences are also reduced. However, when using see-through binocular HMDs, as in a helicopter, convergence issues primarily apply in personal space within the cockpit. Leibowitz (1966) showed that the *greatest* effects of accommodation and convergence on apparent size operate at distances of one meter or less. When see-through HMDs are used in surgery there can consequently be very noticeable effects.

One factor that is of particular importance with HMDs and their use is the dominance of particular cues for distance. In general, accommodation and convergence have marginal or low dominance. This makes adaptation to a HMD much easier when the normal relation between accommodation and convergence is interrupted. Although this uncoupling can cause considerable discomfort, depending on the particular HMD under consideration, users visually adapt to use fairly well (Mon-Williams and Wann, 1998; Peli, 1995)

An issue that has been the source of much debate is whether visual space is best described as Euclidean or non-Euclidean (Wagner, 2006a). Euclidean geometry describes the local objective space we operate in and comes close, with considerable variability, to describing the visual space used in distance estimations. However, Wagner (2006b) concludes, after extensive review of the experimental literature, that our visual space and physical space are simply not the same. It may well be that Euclidean geometry best describes the space we constantly strive to approximate in our efforts to correctly constrain behavior.

The relationship between behavior and perception is not simple. Perception does not define behavior and is not the only thing that constrains it. A good example is the piloting of a helicopter. The relation between visual inputs, our perception of the world, our memory, our learned patterns of behavior, and the cognitive framework we are using all combine to help us perform some very subtle and indirect movements necessary to accurately guide the flight of a helicopter (Zalevski, Meehan and Hughes, 2001).

So, what is size constancy, and how is it important to the use of HMDs? It is a category of visual perceptions arrived at through multiple sources of information that are opportunistically assembled from moment to moment. We use our senses, our cognitive abilities, our memories, and our information to determine whether an object viewed at varying distances, from various perspectives and from various orientations is the same unvarying object in size and shape. This is important for our navigation through the environment, the identification of objects, the avoidance of harm, and the precise applications of our behavior. It is important that we be accurate and flexible enough to adapt to continuously changing environments, and it is fair to say that we have been.

HMDs affect our ability to assemble sources of information and thereby evaluate the layout of objects in our environment. The challenge to design engineers is to make the process as "transparent" (as easy and reliable) as possible.

Visual Acuity

Webster's Ninth New Collegiate Dictionary defines normal VA as the relative ability of the visual organs (eyes) to resolve detail that is usually expressed as the reciprocal of the minimum angular separation in minutes (of arc) of two lines just resolvable as separate and that forms in the average human eye an angle of one minute (of arc). The words in parenthesis were added for clarity. There are two important points that should be noted in this definition: 1) VA is a characteristic of the human eye and 2) the average (normal) human eye can resolve detail to about one minute of arc. The first point will be explored further in this section and the second point is addressed in a later section. (See Chapter 7, *Visual Function*, for addition reading on VA.)

It is apparent from this dictionary definition of VA that this parameter is a characteristic of the human eye that relates to the ability of the human eye to see detail. There is no mention of night vision goggles NVGs), HMDs, or other intervening viewing devices. In fact, implicit in the definition is the assumption that the only significant factor that affects the resolvability of the two lines is the human eye’s ability. How, then, can this parameter be used to describe a quality characteristic of a viewing device of HMDs such as the IHADSS and NVGs?

It is not uncommon to see reference to the “VA” of an HMD as a way to describe how good the display (and sensor) system performs. Usually, some viewing conditions are included within the VA statement such as: “This NVG has a VA of 20/25 under optimum light conditions and 20/50 under starlight conditions.” Strictly speaking, NVGs and other HMDs do not have, and cannot have, a VA, since they are nothing more than an image transducer or a viewing device. What is really meant when one refers to the VA of an HMD is that this is the expected VA of a normal observer when viewing through the HMD under the conditions described, since the concerns of interest usually revolve around the human-NVG system capability as a whole. This may seem like an unimportant, subtle difference, but it can have a real impact if one does not understand this difference. The implications of this difference will be addressed further in the section on measuring VA through NVGs.

The characterization of image quality of most displays, including HMDs (other than NVGs) usually includes some parameter that relates to the display’s capability to produce detail. Such parameters as resolution, number of pixels, pixel pitch or modulation transfer function (MTF) are used to convey information regarding the level of detail that one can expect the display to produce. Although NVGs contain image intensifier (I^2) tubes that are often characterized by their resolution or MTF, the NVG itself is almost always characterized by stating the VA. Even though this is something of a misnomer, if properly accomplished and reported, the “visual acuity of the NVG” (VA that can be achieved when viewing through the NVG) can be a useful parameter when comparing NVGs or determining what visual tasks can be accomplished using the NVGs.

Regardless of the potential usefulness or potential for error associated with the concept of VA of NVGs, it is a fact of life that it is a parameter that is often used and reported in the NVG community as a means of conveying information regarding the quality of the NVG, and it is not likely to disappear from usage any time soon. It can be a useful tool for comparing two NVGs and it can be a misleading factor if not properly understood. It is therefore important to understand what is meant by “visual acuity of the NVGs,” how it is measured, what units are used and how to convert between them, what affects it and how accurate it is. These are explored in the following sections.

Converting between visual acuity units used for HMDs

The definition cited above states that VA is the reciprocal of the separation of two lines, expressed in minutes of arc that can just be resolved by the eye. So, if two lines are separated by just one minute of arc when they are resolved then the VA would be 1 (no units) and if the separation were two minutes of arc, the VA is 0.5 and so forth. The reason for defining VA in terms of the reciprocal is to make larger numbers correspond to better capability (i.e., finer detail can be resolved). Although visual scientists tend to use this specific measure of VA, it is rarely used within the NVG and HMD communities. There are many different vision test charts and measurement units that are commonly used in assessing the VA of NVGs. This section describes the three most common measurement units and how to convert between them. Later sections describe the different vision charts and measurement procedures that are, or have been, used.

Three common units for specifying VA (through NVGs) are Snellen acuity (20/xx),[2] cycles per milliradian, and cycles per degree. Snellen acuity was primarily developed for fitting eye glasses and is normally associated with a vision chart composed of rows of letters that get smaller as one looks farther down the chart (Figure 10-9). Snellen acuity is always stated as the ratio of two numbers such as 20/20 (read as "twenty-twenty") or 20/40 (read as "twenty-forty"). The first number is the distance in feet that a test subject can read a particular chart line and the second number is the distance in feet that a "normal" person could see that same line. So, for example, if an individual can only see 20/40, this means he/she has to be 20 feet away from something that a normal person could see at 40 feet (twice as far away). In Europe the two numbers are based on the observation distance in meters instead of feet, and the first number is 6 (corresponding to 6 meters). Snellen acuity of 20/20 (normal vision) corresponds to Snellen acuity of 6/6 in European format.

Figure 10-9. Snellen vision chart.

Snellen acuity is based on the assumption that a normal person can resolve high contrast detail that subtends one minute of arc (there are 60 arc minutes in 1°). This way of referring to VA is particularly popular with the users of NVGs, since they typically have a comfortable familiarity with Snellen acuity from their eye exams. Note that for Snellen units, the larger the denominator, the poorer the VA.

A second common unit of VA that is typically used by engineers in specifying and characterizing the NVGs is *cycles per milliradian*. This type of measure normally relates to a periodic type of vision chart such as a square-wave pattern or sine-wave pattern (Figure 10-10). A cycle refers to one dark and one bright bar of the pattern. So if the periodic vision chart were viewed from a distance such that the width of one dark bar plus the width of one light bar of the pattern subtends 1 milliradian, then the pattern would correspond to 1 cycle per milliradian.

---

[2] A number of tests have been developed for measuring visual acuity, but *Snellen acuity* has remained the standard. It does however have limitations. It also is important to note that many individuals can have better than 20/20 (6/6) "normal" vision.

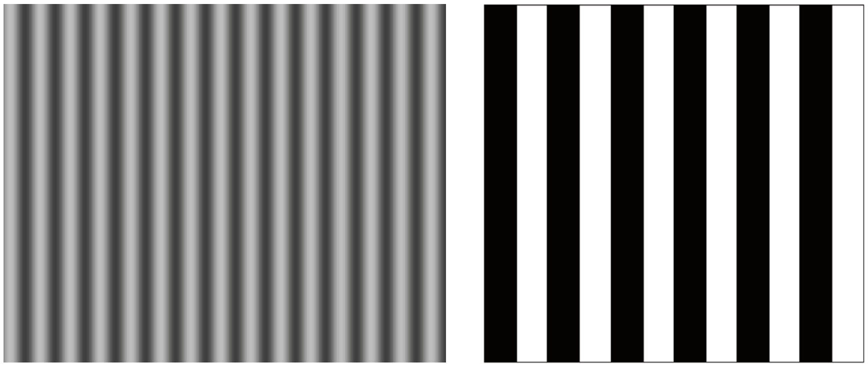


Figure 10-10. Sine-wave (left) and square-wave gratings (right).

The third unit that is occasionally used to characterize VA is *cycles per degree*. This unit is most commonly used by individuals that have a visual science background. Like the cycles per milliradian unit discussed above, it is also normally related to a periodic type of vision test chart. One cycle per degree means that one dark bar plus one light bar of the pattern subtends 1°.

While these different measures of VA were originally based on different types of vision test charts, it is possible to convert from one type of measure to another using certain widely-accepted assumptions. The basic assumption is that the minimum resolvable detail for normal vision is one minute of arc. The additional assumptions are that it takes two minutes of arc to resolve one cycle of a periodic pattern type vision chart, and that it takes five minutes of arc to resolve a Snellen letter. Using these assumptions, it is possible to derive equations that allow useful conversions between the different VA units. A convenient table for convert from one of these VA units to another is available in Barfield and Furness (1995).

Measuring visual acuity through NVGs

The term "resolution" is defined (the definition of interest for this topic) by Webster's Ninth New Collegiate Dictionary as "the process or capability of making distinguishable the individual parts of an object, closely adjacent optical images, or sources of light." As noted earlier, the same dictionary defines "visual acuity" as "the relative ability of the visual organ to resolve detail that is usually expressed as the reciprocal of the minimum angular separation in minutes of two lines just resolvable as separate and that forms in the average human eye an angle of one minute." It is apparent from these two definitions that "resolution" and "visual acuity" are connected but are not quite the same thing. This is, in effect, the difference between the VA "of" the NVGs (actually, the *resolution* of the NVGs) and VA "viewing through" the NVGs.

There is a subtle, but very real, difference between "NVG resolution" and "visual acuity through NVGs." This can be demonstrated by the following example. Suppose that some day advanced technology produces a "super" NVG capable of producing details down to a tenth of a minute of arc (well beyond normal human vision). If unaided (no magnification) vision is used to assess these "super" NVGs, we would get a reading of about 1 minute of arc (20/20 Snellen), since that is the limit of visual capability; even though the NVGs were producing details down to one tenth of this size (20/2). Thus, in this case, what is being measured is actually VA "through" NVGs and not the actual NVG resolution. As long as NVG capability is worse than human visual capability, there is not a significant difference between the two. However, even with today's NVGs, the difference between NVG resolution and NVG VA can be significant at low light levels. There are many combinations of vision test charts and assessment procedures that are used to determine NVG VA.

The Snellen chart displays rows of high contrast letters starting with a very large size (e.g. 20/200) and stepping down to the smallest (e.g. 20/10). Miller et al., (1984) used the Snellen eye chart to measure VA through NVGs.

The tumbling E (used by Wiley, 1989; Levine and Rash, 1989) chart has also been used to measure VA through NVGs. Some researchers (Kotulak and Rash, 1992) prefer to use the Bailey and Lovie (1976) eye chart, which has logarithmically spaced letter sizes.

One of the most frequently used resolution test standards is the 1951 Air Force tri-bar target (see Figure 12-11), which was originally developed as a tool to evaluate the optical performance of airborne reconnaissance systems (Military Handbook 141, MIL-HDBK-141, Defense Supply Agency [1962]). A conversion factor must be used to convert from the *Group* and *Element* number of the tri-bar chart to NVG VA.

NVG VA is determined by having a visually qualified, trained observer view the tri-bar pattern under specified illumination conditions (which may be between overcast starlight up to full moon illumination equivalent) and then state which Group and Element number he/she can "resolve." This is then converted to a Snellen acuity equivalent. When doing NVG evaluations, agencies may have 3 trained observers whose responses to this test are averaged to determine the "visual acuity" of the night vision goggles. Although the 1951 tri-bar target pattern has proved to be very useful over the years in comparing lens systems, it still has a certain amount of variance due to differences in observer criteria as to when the tri-bars are "resolved" (Farrell and Booth, 1984). Studies using the tri-bar pattern have shown observer response discrepancies of as much as 60% (Farrell and Booth, 1984).

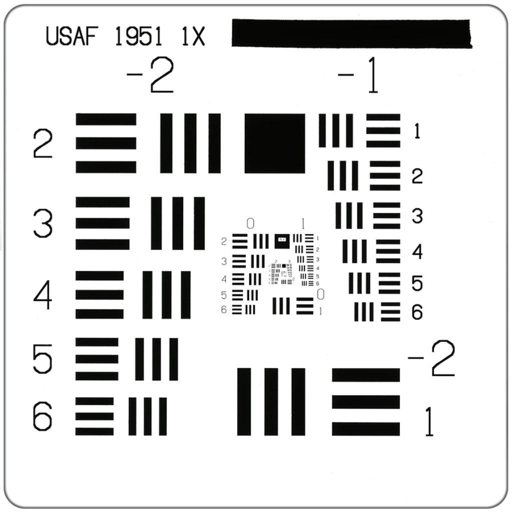


Figure 10-11. Air Force 1951 tri-bar resolution chart.

The 3x3 square-wave target array (Task and Genco, 1986) was developed as a means for pilots to do a quick verification that their NVGs were operating correctly and were capable of resolving detail to a specified level. The chart has nine square-wave patterns, arranged in a 3x3 array as shown in Figure 10-12 its standardized viewing distance of 20 ft., each pattern was sized to equal specific Snellen values of 20/20 through 20/60 in increments of five. To increase the number of randomized grating orientations for a repeated measurements test, the chart is simply rotated to any one of its four orientations, which has the effect of quickly changing grating locations and orientations within the 3x3 array. Charts having different levels of contrast were also constructed.

It should be noted that the step sizes between patterns are relatively large making this pattern unsuitable for comparing the capability of different NVGs that are somewhat close in their resolving power (i.e., VA).

An array of square-wave gratings to assess VA is also used in the Hoffman 20/20^{TM} device. This device was designed for aircrew members to adjust their NVGs and verify that they have the minimum VA through the NVGs prior to flight (Angel, 2002). Figure 10-13 shows the device and the square-wave grating patterns that it displays. The gratings correspond to Snellen visual acuities of 20/20 through 20/70 with step sizes as shown. This is a subjective assessment method that is often used to determine the VA of the NVGs.

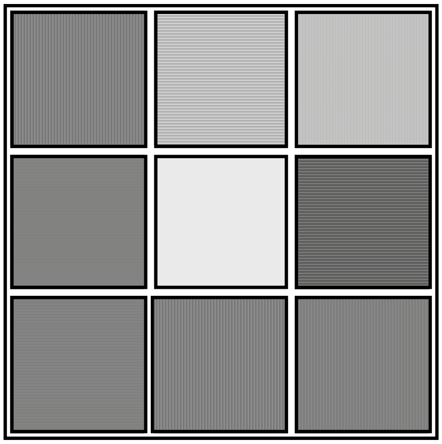


Figure 10-12. The 3x3 NVG chart (Task and Genco, 1986, US Patent 4,607,923).

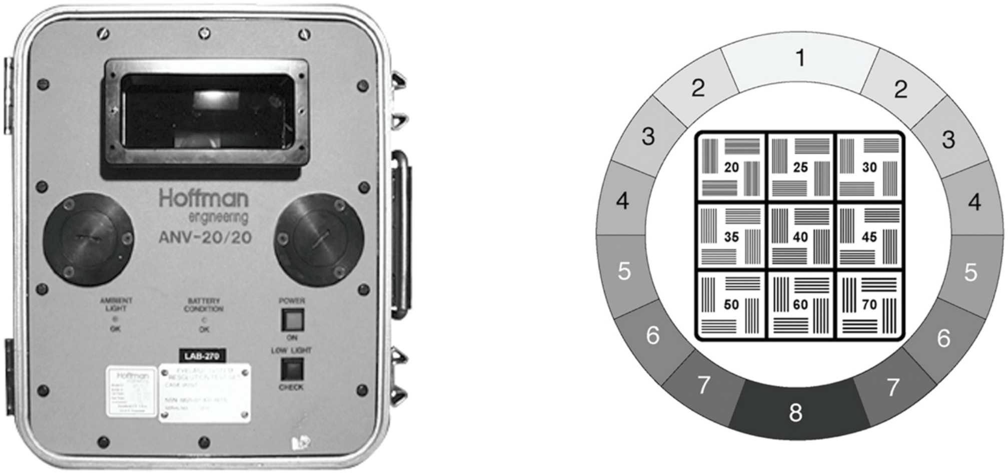


Figure 10-13. Hoffman Engineering ANV-20/20™ device (left) used to pre-flight NVGs. Pattern on the right is the array of square-wave gratings that is seen through the NVGs when the NVG objective lenses are positioned in front of the large, rectangular viewing port visible at the top of the picture on the left.

Another assessment method uses Landolt C stimuli (National Academy of Sciences, 1980). The Landolt C is a perfectly circular C (no serifs) that has a specified contrast and gap size. The gap size is varied as is the orientation. The observer's task is to detect the orientation of the gap. Pinkus and Task (1997) used closely sized Landolt C stimuli in a two-alternative, forced-choice (2AFC) method to determine VA through NVGs as a function of nighttime ambient illumination levels. A computer executed the 2AFC (gap seen up or down), using a Step Program adapted from Simpson (1989). Based on the observer's last response, the program selected the specific gap size (smaller or larger) of the next Landolt C to be presented, according to *a priori* rules inherent in the algorithm. This method allowed relatively efficient convergence to threshold acuity usually within 10 to 35 trials. The step method yielded reasonable results, but informal repeatability tests found that the observer's scores varied from day to day. These variations could be due to a number of variables: working at threshold levels, NVG drift, good guessing in the 2AFC method, fatigue, eye strain, sinus headaches and so on.

In summary, there have been numerous test charts and targets to assess VA including the Snellen chart, square-wave gratings, sine-wave gratings, tumbling E, 1951 USAF Tri-Bar chart and Landolt C. These have been used with several assessment procedures including both objective procedures and subjective procedures. The quasi-objective procedures, such as the two-alternative forced-choice method described above, require the subject to provide information about the target type that would only be reliably available if the subject could actually "resolve" the critical characteristic of the target type used. For example, which way the gap is oriented in a Landolt C or which way the arms of the E are pointed in a tumbling E target. Subjective measures involve the subject making a judgment that they can or cannot resolve the critical detail of the target. An example of a subjective assessment procedure is when a subject reports which group and element number of a USAF 1951 Tri-Bar chart he/she can just barely resolve. In general, objective tests should provide more accurate data but take much longer to accomplish. Both subjective and objective assessment results can depend heavily on the specific subjects that participate in the assessments. In general, better results are obtained if more subjects are used in the assessment (ideally at least 3, if possible) and the subjects are trained or have substantial experience in the assessment procedure.

Measuring visual acuity through HMDs connected to remote sensors

A person seldom sees explicit references to the VA of a HMD that is connected to a remote sensor, such as the IHADSS HMD on the AH-64 Apache helicopter. However, providing an acuity value for thermal forward-looking infrared (FLIR) sensor-based systems (e.g., the AH-64's Pilot's Night Vision System [PNVS]) is difficult since the parameter of target angular subtense is confounded by the emission characteristics of the target being viewed. This is not unlike the difficulty of determining the VA through NVGs for different ambient lighting conditions (see following section on conditions affecting NVG VA results). For comparison purposes, Snellen VA with the AH-64 PNVS/IHADSS is cited as being 20/60 (Greene, 1988).

Whether the sensor is a FLIR or a low light level TV or a short-wave infrared (SWIR) device the primary determinant of what one can expect in the way of VA (ability to see detail) is typically a combination of the capability of the HMD optics and image source with the sensor optics and detector array. If the FOV of the sensor is identical to the FOV of the HMD (which it should be for piloting-type tasks) then the VA expected through the system is determined by the angular subtense of the smallest detail that can be resolved through the entire system compared to one minute of arc. In the case of the AH-64 PNVS/IHADSS (HMD and sensor have the same FOV), which had a Snellen acuity of 20/60 (noted above), the observer was presumably able to resolve details to approximately three minutes of arc.

In the unusual situation where the sensor FOV is not the same as the HMD FOV (such as systems that produce magnification by making the sensor FOV narrower than the HMD FOV), there is can be an ambiguity in determining the effective VA. The basic issue is whether to use one minute of arc in the HMD FOV as a reference or one minute of arc in the actual, real world geometry as a basis. For example, if the sensor FOV was 1/5th of the HMD FOV (producing a magnification of 5X) and the sensor could resolve objects that were one arc minute in size as measured from the sensor then this would subtend 5 minutes of arc in the HMD. So, should the "visual acuity" be stated as 20/100 (HMD FOV referenced) or as 20/20 (real world geometry referenced)? There are arguments for each way that are beyond the scope of this discussion. Suffice it to say that if the system provides magnification with respect to the real world, then it is necessary to always state which reference (HMD FOV or real world geometry) was used to quote the "visual acuity" of the HMD-sensor system.

Conditions affecting NVG visual acuity results

The primary reason for measuring NVG VA is to obtain information regarding the image quality capability of the NVG. However, because the assessment procedure involves not only the NVGs but also a human observer and is accomplished under some ambient or artificial environmental conditions, the results are due to the combination of these three factors. There are several parameters contained within each of these factors that can affect the NVG VA results obtained, as noted in the following sections.

NVG parameters that can affect NVG visual acuity

Gain, maximum luminance, signal to noise ratio (SNR), objective lens quality (e.g., MTF), objective lens focus setting, I^2 tube micro-channel plate pitch, fiber optics twister (if any) quality, eyepiece lens MTF, eyepiece focus setting (diopter adjustment), and eye motion box size and quality can all affect the results obtained when assessing VA through NVGs (Figures 10-14). While all of these parameters are fundamental characteristics of the NVG, only a few of them have an effect on the NVG VA assessment that is totally independent of the human observer. Most of them involve an interaction with the way in which the human eye operates.

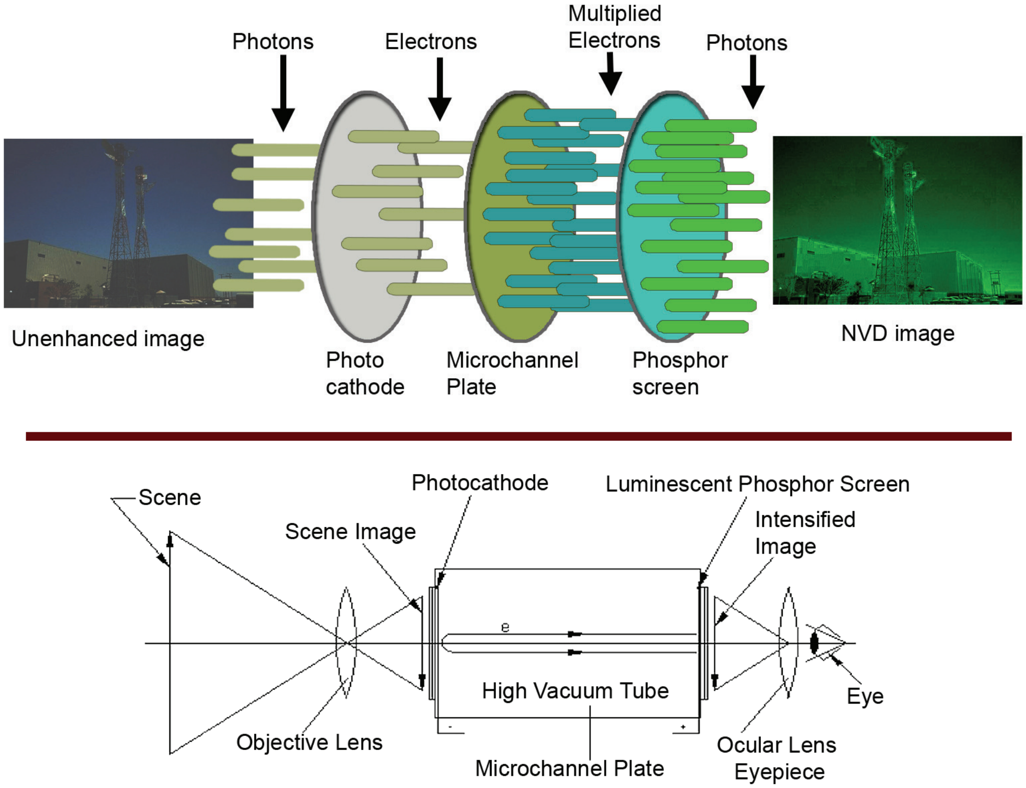


Figure 10-14. Operation of an image intensifier tube.

The gain of an NVG is the ratio of the input luminance to the output luminance for a light source that has a spectral distribution equivalent to a 2856K° blackbody emitter. This is actually an oversimplification of NVG gain, but the main point here is that, in general, the output luminance (what the eye is going to see) is higher for NVGs that have higher gain values for the same input (ambient scene) radiance. This assumes that the ambient radiance conditions are low enough that the I^2 tube within the NVG is operating at maximum gain (the automatic gain control circuitry is not activated). Under these conditions, NVGs with higher gain will have a higher output luminance. Since at these low NVG output luminance levels (on the order of a few thousandths to a few tenths of a foot-Lambert [fL]), the VA of the human eye is improved as luminance is increased, it is apparent that VA is better with higher NVG gain.

The maximum output luminance of the NVG is typically determined by circuitry within the I^2 tube power supply system, which limits total current to some maximum value. If there is sufficient ambient radiance that this circuitry is activated, then NVGs with a higher maximum output luminance should result in better VA for the reason stated above.

The SNR of the NVG is a result of several factors. In general, the higher the SNR the better VA one will obtain (Riegler et. al., 1991) since the masking effect of the noise is reduced.

The imaging quality of the objective lens of the NVG oculars can also affect the resultant VA. The objective lens (the lenses on the front of the NVGs) produces an image of the outside world scene onto the photo-cathode of the image intensifier tube. The "sharpness" of this image depends chiefly on MTF[3] of the objective lens, and in general, the better the MTF, the better the VA (up to a point). It should also be noted that the MTF is typically different for different parts of the image. In general, the MTF is better at the center of the image and becomes worse as one looks further out from the center of the image towards the edges. This is often the main reason that the VA obtained through NVGs is better in the center of the image than at the edges (other factors typically don't vary across the image as much as the MTF does).

Another factor that can have a significant effect on the VA through the NVGs is the objective lens focus setting (Pinkus and Task, 2000). Because of the very low f-numbers (ratio of focal length of lens to the diameter of the lens), the "sharpness" of the image produced by the objective lens can suffer significantly if the focus adjustment isn't set correctly. Note that this is not the same as the MTF (which is determined under the assumption that the focus setting is correct). However, the focus adjustment effect on the VA is similar; namely, it produces a blurry image on the photo-cathode of the I^2 tube for which nothing else in the imaging chain can compensate.

At the heart of the image intensifier of present day NVGs is a micro-channel plate (MCP) that is the workhorse in amplifying the image signal. The MCP is a thin disc that has many thousands of tiny holes each of which acts like a miniature photo-multiplier tube. These individual holes are essentially the *pixels* (picture elements) of the I^2 tube. Although there is an interaction with the eyepiece lens focal length, in general, the more holes the MCP has and/or the closer together these holes are, then the better the VA obtained when viewing through the NVGs.

Most NVGs produced today require a fiber optics *twister* to produce an image that appears upright to the viewer. As its name implies, this twister rotates the output image 180° (±) with respect to the input image. It does this by means of thousands of tiny fibers each one of which could be considered a pixel similar to the MCP holes. In general, the closer these fibers are to each other (achieved through smaller fiber diameters) the better VA one should obtain. It should be noted that typically the quality and size of the fiber optics twisters currently produced result in a much better pixel count and pixel pitch (basically the distance between individual pixels) than the MCP. This means that typically the fiber optics twister is not a significant factor in limiting VA through NVGs, although it theoretically could be.

The eyepiece lens is the final lens in the NVG optical train and is the lens the eye looks through to see the output image from the I^2 tube. Just like the objective lens, the eyepiece lens has an MTF that can influence VA. Because of the limiting effects of the human eye's entrance pupil, the impact of the eyepiece lens MTF on VA is usually not significant. However, if the eye's pupil is not positioned along the center of the optical axis of the eyepiece lens, one can experience a rapid deterioration of the MTF. This is related to the concept of the *eye motion box*, which is the zone within which the eye pupil should be positioned in order to have an acceptable level of image quality. Outside of this zone the MTF can drop off rapidly resulting in poor or blurry image quality corresponding to worse VA. In general, better VA is obtained for eyepieces with better MTFs and with larger eye motion boxes.

Many NVGs currently produced permit the operator to adjust the eyepiece focus. This is also frequently called the diopter adjustment or diopter setting. The eyepiece lens produces a virtual image of the output of the I^2 tube. The apparent distance of this image from the viewer is determined by the eyepiece diopter setting. The apparent distance in meters is calculated by taking the reciprocal of the diopter setting value. For example, if the diopter setting is one diopter, the image will appear to be one meter away. Similarly, if the diopter setting is two diopters

---

[3] The modulation transfer function (MTF) is defined in this context as the sine-wave spatial-frequency amplitude response used as a measure of the resolution and contrast transfer of an imaging component, device or system.

the image will appear to be only 0.5 meter away (i.e., the reciprocal of two). This parameter of the NVG interacts with the viewer's ability to focus at the apparent distance associated with the diopter setting. There also may be some minor interaction with the MTF of the lens since this typically varies a small amount depending on the diopter setting. In general, VA improves as the diopter setting is adjusted correctly for a particular user's eyes (Angel and Baldwin, 2004; Angel, 2003).

Although all of the parameters covered in this section relate directly to the characteristics of the NVGs, it is also apparent that many of them interact with the characteristics of vision. In general, better VA is obtained for NVGs with higher gain, higher SNR, better objective lens/eyepiece lens MTF, higher density holes in the MCP, higher density fibers in the fiber optics twister, better adjusted objective (focus) and eyepiece (image distance) settings, and optimized eye position within the eye motion box.

Human vision parameters (of the observer) that affect NVG visual acuity

Since the human visual system is an obvious integral part of any VA assessment through NVGs, it should be apparent that the visual capability of the specific user(s) is critical. Ideally, users should have excellent VA at the relatively low NVG output light levels (luminance of a few fL at most), since the objective of the test is to assess the NVGs, not the subject's vision. Other factors besides the user's innate VA (without NVGs) can also affect the test results. These include the user's dark adaptation state at the time of the test and whether or not the test is conducted binocularly (both eyes and NVG channels test simultaneously) or monocularly (testing one NVG channel at a time).[4]

A significant factor that can affect the VA obtained for an individual is the adaptation state. It takes the human eye a certain amount of time to recover (bio-chemically) when switching from a higher light level environment to a lower light level environment. For example, if one enters a movie theater on a bright day the movie screen appears to be very dim until the eyes have had a chance to adapt to the lower light level. The same effect can occur when assessing VA through NVGs if the observers go directly from a lighted room to viewing through the NVGs. Typically, this adaptation issue is resolved by requiring the subject to dark adapt for 10 to 20 minutes.

In addition to the relatively short adaptation state effect discussed above one can also encounter a longer term adaptation effect. If an individual spends a large amount of time during the day exposed to very high light levels, such as spending the day at the beach or snow skiing, then it may take more than just a few minutes to achieve full adaption; it could take several hours. (See Chapter 7, *Visual Function*, for addition reading on visual adaptation.)

There has been some evidence that the effects of smoking, which decreases the oxygen content in the bloodstream and therefore the oxygen getting to the retina, may result in poorer low-light VA compared to non-smokers (see Chapter 16, *Performance Effects Due to Adverse Operational Factors*).

Another significant impact on low-light VA can occur depending on whether or not the VA is being achieved (or measured) binocularly (both eyes at the same time) or monocularly (one eye at a time).[5] This interacts with the NVG characteristics in that if the two channels of an NVG are different because of some physical parameter (such as objective lens focus or MTF) the resultant VA obtained binocularly is typically governed by the image quality of the best NVG channel. In other words, if one conducts a binocular VA on an NVG it is possible to overlook a poor NVG ocular if the other ocular has produces good image quality. There are, therefore, advantages for conducting both binocular and monocular VA assessments of NVGs.

In general, one obtains improved VA values if the individual has good VA capability, is properly dark adapted, is a non-smoker, and the test is conducted binocularly (although, as noted, monocular testing has its own advantages).

---

[4] NVGs have a luminance output (brightness) that falls in the range associated with human *mesopic vision.* Therefore, wearers of NVGs are not fully dark-adapted.

[5] Standard NVGs are binocular, but several I^2-based HMDs have proposed a single tube design.

Environmental parameters that affect NVG visual acuity

Environmental parameters that are independent of both the NVGs and the user can affect the achieved VA. It has already been noted that with NVGs, human VA is better if the light level is higher. This is a fundamental characteristic of the human eye and does not really relate to the NVG's capability to produce a high-resolution image but rather the NVG's capacity to produce luminance. Environmental parameters that can affect the VA achieved with NVGs include NVG radiance level of the vision target and surrounding area, the type of vision target used (Landolt "C," Tri-Bar Chart, square-wave grating, etc.), the apparent contrast of the target (through the NVGs), degradation effects (e.g. glare off of the vision test chart or reflections from a windscreen or canopy), and the distance from the test chart to the NVGs.

The NVG-weighted radiance (Task and Marasco, 2003; 2004) of the vision chart and the gain of the NVGs determine the output luminance level, which in turn can affect the VA obtained (at least for lower radiance levels). Two typical NVG radiance values that are often used for NVG VA evaluation correspond to high moonlight level (full-moon or ¼-moon) and clear starlight. The higher radiance level is sufficiently high so that the NVG is in automatic gain mode and the output luminance is limited to the maximum luminance allowed by the circuitry. At these higher radiance levels, the NVG is providing its maximum output luminance, which is typically in the 2 to 4 fL range depending on the specific image intensifier tube used. At the lower radiance level the output luminance is dependent primarily on the gain of the NVG and is typically on the order of a few tenths of a fL for currently fielded NVGs. Lower input radiance levels that correspond to overcast starlight are also sometimes used resulting in output luminances that can be in the hundredths of a fL range. At these very low output luminance levels, the VA obtained can depend heavily on the low light VA capability of the subject.

The contrast of the vision test chart, and anything that degrades that contrast (glare and reflections), can significantly affect the NVG VA value obtained (Pinkus et. al., 2003). Test procedures for conducting a VA assessment through NVGs typically call for "high" (Department of Defense, 2001) or "medium" contrast charts.

In summary, all of the vision test charts and assessment procedures discussed in this section are useful and can provide some insight into the quality of NVGs or HMD systems. However, it cannot be stressed enough that these multiple VA test charts and procedures can produce different VA values for the same NVG or HMD. Therefore, while any of these procedures can be useful to compare NVGs or HMD systems, care must be taken when comparing VA values for different NVGs and HMDs if they were determined using different procedures and charts (and observers!).

Contrast Sensitivity

Exceptional vision is necessary to achieve high levels of performance under a wide range of viewing conditions. While all human senses are important to the Warfighter, vision is the only sensory system that is used to its fullest capacity during flight tasks (Swamy, 2002). Advances in HMDs allow Warfighters continuous 24-hour, all-weather operation (e.g., night and foul-weather) by using imaging sensor systems on aircraft, mounted vehicles, as well as on individual Warfighters. However, the amount of visual information that can be conveyed by the HMDs is essentially limited by the capacity of the human visual system to perceive contrast (i.e., difference in luminance). While wearing a HMD, optimum viewing conditions are achieved when the luminance of the display is matched to the capacity of the visual system (i.e., maximally sensitive). Optical devices can improve vision by decreasing the spatial frequency of an image or correcting the optical blur (e.g., glasses, contact lenses, refractive surgery), which results in better contrast at high spatial frequencies. Even though, visual enhancement HMDs provide Warfighters with tactical advantage during extended military operations, they can reduce contrast sensitivity and have the potential to decrease performance.

Although VA is often used to describe the quality of vision (i.e., level of spatial vision), contrast sensitivity appears to be a better indicator of visual performance under both, photopic (i.e., day) and scotopic (i.e., night) conditions; this is especially true for aviators (Rabin, 1993; van de Pol, 2007). The visual system depends on a series of visual channels that gather information regarding the object's size, shape, and contrast. The statistical distribution of these channels matches in general the distribution of important visual objects that humans need to navigate around and manipulate, i.e. it is peaked at about 4 cycles/degree, a factor of 5 below the visual system's highest resolution (i.e., around 20 cycles/degree). The collected information is relayed to the brain to create a complete picture. Unlike VA, that tests only one type of these visual channels, a contrast sensitivity test assesses multiple channels that are required to achieve exceptional functional vision. Thus, the visual function is not just acuity (resolution), but includes a combination of complex optical and neural aspects of our visual system. For example, an observer who has low contrast sensitivity may be able to read the small print on an eye chart but may still experience trouble seeing objects at night or in dim tactical or operational conditions. Accordingly, as a metric for spatial vision performance, contrast sensitivity can provide a more comprehensive index of visual function than VA, mainly because most "real world" visual scenes comprise a complex combination of *contrasts* and *spatial frequencies*, instead of isolated high-contrast/high-spatial frequency stimuli that are displayed in a VA test.

Contrast

In real situations, objects and their surroundings are of varying contrast. The ability of an observer to perceive the details of a scene is limited by the capacity of the visual system to discern contrast. As described in Chapter 7, *Visual Function*, a high contrast grating is always easier to see than low contrast gratings. The visual system achieved this level of perception by discriminating between luminosities of different levels in an image. The minimum contrast required to reliably detect the object from its background is known as the spatial contrast threshold. Contrast threshold is affected by several factors such as target size, background luminance, and viewing duration. Contrast threshold is the reciprocal of the contrast sensitivity, therefore the lower the contrast threshold the higher the contrast sensitivity and visual performance.

Optimum contrast and luminance of the imagery is required to optimize visual performance and prevent perceptual problems when wearing an HMD. In order for the symbology to be viewed in a see-through HMD or head-up display (HUD), the luminance of the symbology must be sufficient to discriminate it from the see-through real world scene (Harding, 2007). In addition, to prevent perceptual problems, both the virtual image projected on the see-through combiner lens of the HMD (e.g., Integrated Helmet and Display Sighting System used on the AH-64 Apache helicopter) and the real world scene must be clearly visible at the same time. In order to see both views clearly, they must be within the pilot's depth of field. The depth of field is the range of distances within which the different objects appear in sharp focus (Patterson, 2006) and this in turn will be affected by the focal distance at which the HMD has been set. As long as the optics of the HMD are collimated so that the images appear to lie at or near optical infinity, similar to the real world scene, both the virtual image and the real world scene will fall within the observer's depth of field and perceived to be in focus. When this is achieved, the virtual image will appear as being on the same plane as the real world scene (i.e., overlapping). The level of luminance also affects the depth of field. A decreased luminance level of the HMD induces a larger pupil diameter, which in turn results in a smaller depth of field (Ogle and Schwartz, 1959).

According to the Michelson definition of contrast, a minimum contrast (i.e., luminance ratio) level of 0.10 is required to discriminate the object from its background. Accordingly, if the monochrome imagery displayed on the HMD is viewed against the real world scene under scotopic conditions, the luminance of the image source must exceed 5,000 foot-Lamberts in order for the symbology to be discerned from its background created by the real world scene (Velger, 1998). In addition, the complexity of the real world scene in terms of contrast must be taken in consideration when determining the luminance specifications for HMDs (Harding, 2007). It has been suggested that the use of color symbology in HMDs has the potential to provide the Warfighter with a substantial operational advantage compared to the monochrome symbology (Martinsen and Havig, 2002). Although the development of color symbology is still ongoing, this technology is more complex and may require a tradeoff in resolution and luminance contrast in order to allow recognition of color symbology (Havig et al., 2001).

Spatial frequency

Contrast sensitivity is also dependent upon the size or spatial frequency of the features in the image. The visual system is more sensitive to contrast at certain spatial frequencies. The highest spatial frequency humans can see at any contrast is limited by the optical process. The concept of an optical transfer from the imaging system to the neural processing system has led to the development of the contrast sensitivity function (CSF). The CSF measures relative sensitivity versus spatial frequency and is accepted as a measure of assessing visual performance. Generally, high spatial frequencies gradients are harder to visualize than low spatial frequencies. However, this is not a direct relationship, as in some cases larger objects (lower spatial frequencies) are not always easier to see than smaller objects, as illustrated in Figure 10-15. This is also demonstrated by the CSF (Figure 7-11, Chapter 7, *Visual Function*) in which the sensitivity of the visual system to detect contrast decreases for lower and higher spatial frequencies. In those cases where the size of the object is not optimum—spatial frequency below two and above six cycles per degree (cpd) – the object's contrast needs to be increased in order to be discerned from the background. However, under photopic conditions, frequencies higher than 40 cpd are undetectable even at maximum contrast.

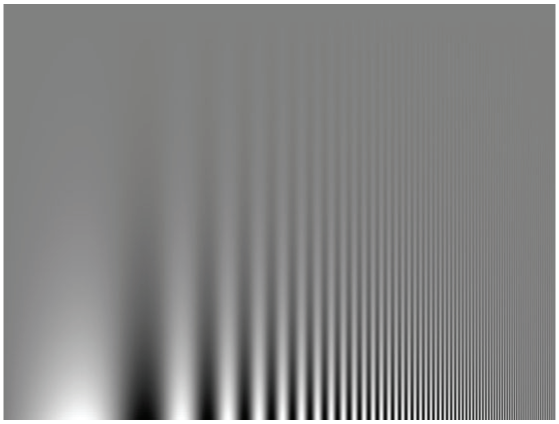


Figure 10-15. The human visual system is more sensitive to middle spatial frequencies. This illustration depicts a sine-wave grating in which spatial frequency increases exponentially from left to right, and the contrast increases logarithmically from 100% at the bottom to 0.5% at the top. At the top, the contrast is too low to see the grating to the point that only homogeneous grey is seen. Very wide (low spatial frequency) and very thin (high spatial frequency) gratings are harder to see than the middle bars, even with high contrast. (Courtesy of Dr. Izumi Ohzawa, University of California, School of Optometry). This figure was originally produced by F.W. Campbell and J.G. Robson, Applications of Fourier Analysis to the visible of gratings, *Journal of Physiology* (Campbell and Robson, 1968).

Scotopic contrast sensitivity

There is a marked difference between spatial contrast sensitivity under photopic and scotopic conditions. For instance, under scotopic conditions, frequencies higher than 8 cpd are undetectable even at maximum contrast. The contrast sensitivity of an aviator while wearing its night vision imaging systems (i.e., ANVIS) is decreased further by a factor of two over a range of spatial frequencies even under optimal ambient levels of illumination. Contrast sensitivity also is decreased considerably with decreasing night sky illumination. The sensitivity loss resulting from decreased ambient illumination is observed across all spatial frequencies; however, this effect is slightly greater for higher spatial frequencies (Rabin, 1993; Wiley and Holly, 1976). This reduction in contrast sensitivity with decreased night sky illumination was found to be a combined effect of lower display luminance and increased electro-optical noise. Rabin (1993) suggested that the development of image intensifiers will improve visual performance by providing greater display luminance and lower noise at starlight and overcast level of illumination. Measures of contrast sensitivity are useful in assessing the potential degradation of visual capability from visual enhancement and visual protection devices used by the Warfighters.

Aging and contrast sensitivity

Contrast sensitivity can become an issue as the Warfighter ages. Contrast sensitivity varies between individuals, reaching maximum at approximately 20 years of age and at spatial frequencies of about 2-5 cpd (Figure 10-16). Aging affects the visual system, which in turn affects the way the visual system and the brain process the collected information. Changes in both the optics and neurons of the eye are the primary causes of reduction of contrast sensitivity with age. With aging, the pupil decreases in size, and the intraocular crystalline lens becomes less transparent. These changes act to reduce the amount of light reaching the retina. Higher-order aberrations also have been associated with age-related cataract development and decreased CSF. Neural changes, such as a reduction of the number of retinal ganglion cells, also can have substantial impact on the observers contrast sensitivity. Accordingly, measures of contrast sensitivity are valuable predictors of the physiological and pathological status of the visual system. In particular, the shape and the height of the CSF can predict if an individual is prone to having difficulties seeing visual targets. Owsley and Sloane (1987) showed that the best predictors of thresholds for real world targets are age and visual function in the middle to low spatial frequencies. Therefore, an understanding of the anatomical and physiological limitations of the visual system is imperative to maximize the contrast required for optimum performance while wearing an HMD.

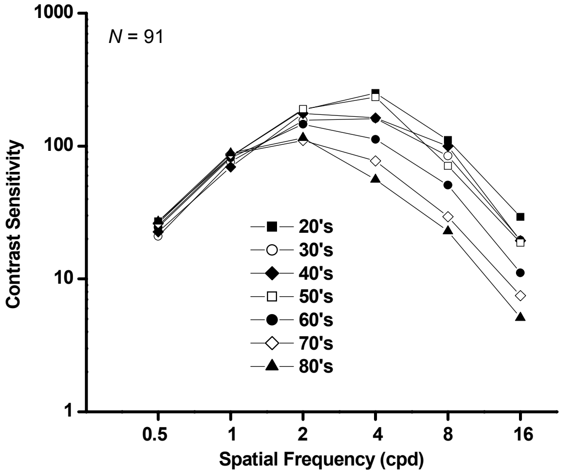


Figure 10-16**.** The contrast sensitivity function (CSF) demonstrates decreased contrast sensitivity as a function of age at middle and high spatial frequencies in cycles per degree (cpd) (adapted from data published [Owsley, 1983] with permission of Dr. Cynthia Owsley).

Effect of refractive surgery on contrast sensitivity

Vision correction by refractive surgery, similar to the use of contact lenses, help to overcome most of the interface problems—e.g., comfort, restricted FOV, lens reflections and glare—usually introduced by spectacles while wearing HMDs. Vision correction by refractive surgery further solves the problems induced by contact lenses wear such as contact lens intolerance, tearing, lens dislodging, lower VA that with spectacles, difficulty of lens hygiene and professional care in the field environment as well as the increased risk for corneal infections (Rash, 2002). Contrast improvement at high spatial frequencies by surgical correction of the optical blur has a positive effect on vision and flight performance under low contrast and low luminance conditions typically encountered in flying conditions. Among the most common surgical procedures undergone by U.S. Army aviators to correct their refractive error are photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK). Conventional PRK and LASIK correct first and second lower-order aberrations—such as myopia, hyperopia, and astigmatism. However, they induce higher-order optical aberrations that positively correlate with the amount of myopia correction (Mrochen, 2001). In particular, coma-like aberrations have been shown to influence the contrast sensitivity function. An increase in the aberrations of the eye following refractive surgery also is associated with difficulties with night vision, halos, and glare (Bailey, 2003; Fan-Paul, 2002).

There are conflicting reports regarding the effect of refractive surgery on contrast sensitivity. Some studies have demonstrated that the CSF is compromised by refractive surgery, to include PRK and LASIK, and that increases in higher-order aberrations correlate with deterioration of the CSF. A decline in contrast sensitivity and visual performance under glare conditions after PRK (Dennis, 2004) and reduction on contrast sensitivity across a wide range of spatial frequencies after conventional LASIK have argued against the benefit of conventional refractive surgery to improve optical blur over spectacle correction (Yamane, 2004). Conversely, a more recent study evaluating flight performance of pilots after PRK and LASIK under day as well as unaided and aided night (i.e., NVG) conditions, indicates that there is not a significant baseline performance difference between subjects that underwent these procedures (van de Pol, 2007). In addition, the same study shows there is not significant difference in contrast sensitivity between conventional PRK and LASIK subjects one month after surgery. The advent of wavefront- and topography-guided LASIK that corrects both lower- and higher-order aberrations has resulted in significant improvement in contrast sensitivity and visual performance compared with conventional LASIK (Kaiserman, 2004).

Importance of contrast sensitivity of target detection

Pioneer work by Ginsburg (1983) demonstrated the usefulness of contrast sensitivity as a metric of reduced visual performance—compared to VA—when viewing through aircraft transparencies. This work determined that reduction in the CSF due to HUDs was correlated to diminished target detection ranges. In a subsequent study, Ginsburg and Easterly (1983) demonstrated that pilots with increased contrast sensitivity were capable of acquiring targets further away than less sensitive observers under similar scotopic conditions. The study also showed that increasing the contrast by a factor of only 1.5 to 2 is required for going from chance detection to definite detection. Therefore, while a highly sensitive pilot is able to see the target definitely, a less sensitive one still may be unsure of its presence. These variations in contrast sensitivity and target detection are critically important, as survival in today’s combat environment can depend on making split second decisions (Swamy, 2002).

Color Discrimination

Color is a characteristic of display elements often used to encode information. While early display technologies generally were monochromatic (having no variation in hue),[6] multicolor displays have recently become the norm for virtually all display technologies.

Normal color vision and the ability to discriminate between colors is essential to the Warfighter who must identify the colors of targets, smoke, flags, signal and navigation lights, and terrain differences (Tredici and Ivan,

---

[6] Monochromatic displays should not be interpreted as black and white, as many of these displays were green on black, red on black, yellow on black, etc.

2008). (A thorough discussion of color vision is presented in Chapter 7, *Visual Function*.) All military services, as well as civil aviation agencies, have color vision requirements, but these requirements have been under scrutiny in recent years. Color vision testing generally has relied on the use of pseudoisochromatic plates and, more recently on the Farnsworth Dichotomous test (an aviation standard). However, color contrast and resulting color discrimination capability under real-world conditions can be affected by environmental conditions (e.g., ambient lighting and the presence of fog and haze) and by physiological conditions (e.g., hypoxia and fatigue).

The ability to discern small color differences is easier when the areas to be discriminated are large, contiguous (share an edge near the viewed point), and are viewed simultaneously (National Aeronautics and Space Administration, 2004). As the viewed areas decrease in size or are separated from each other, discrimination becomes more difficult if not impossible. Color discrimination is greatest when a sharp edge separates the colors to be discriminated, e.g., between a symbol and a uniform background color. When a smooth gradient separates two color areas, the smallest detectable difference in color is larger (National Aeronautics and Space Administration, 2004).

Color discrimination and identification is more difficult when the color areas are small and narrow such as would be the situation for symbols and alphanumeric characters used in displays.

The NASA Color Usage Research Lab[7] has provided the following guidelines for the use of color where discrimination and identification are critical:

- *Use no more than six colors to label graphic elements* – How many can be reliably identified depends on several characteristics of the application. In cockpit and automotive applications the user can afford only a glance at the display as part of a rotation among items that must be monitored, and errors can have severe consequences. Fewer and highly distinct colors must be used in this type of application. On planning displays (e.g., maps, scientific visualizations) the user typically has time to more carefully scrutinize elements and refer to a legend. The consequences of errors are less immediate and more likely to be noticed before there are problems. Often more colors can be used in these cases.
- *Use colors in conformity with cultural conventions* – Some hues have become associated with particular meanings through widespread use or tradition. Red, yellow, and green are associated with safety status. Other uses of these colors can lead to unintended interpretations. In applications where only six-to-eight colors are identifiable this severely restricts the options for color coding of non-safety variables.
- *Use color coding consistently across displays and pages* – Users should not be required to associate different meanings with the same hue in various parts of their work environment. Remembering different interpretations in different contexts increases cognitive effort and opens opportunities for error.
- *Use color coding redundantly with other graphic dimensions* – When user populations may include users with anomalous color vision (8-10% of the population), important information must be identifiable on some basis other than color discrimination. Even for individuals with normal color vision, this can be a valuable design goal.
- *Don't use color coding on small graphic elements* – Color discrimination is better for large areas than for small (e.g., small fonts and symbols). This is more of a concern for *at-a-glance* applications than for those where careful examination is possible. Even in the latter it can slow the user down.
- *Use neutral gray surrounds where color judgments are critical* – Simultaneous and successive color contrast can interfere with accurate color identification.

---

[7] NASA Ames Research Center, Moffett Field, CA.

In military aviation the two longest-fielded HMDs are monochromatic systems: the NVG and the IHADSS. Both present imagery as green on black. Color HMDs have been late in development due mostly to their high cost and weight; color displays also require resolution and luminance tradeoffs. Also, the use of color image sources increases the complexity of the relay optics design, since a polychromatic design must be used. However, these factors have not decreased their desirability to the user. This desirability lies in the fact that color is a very conspicuous attribute of objects. Color can facilitate three functions: Serve as the actual work object, support cognitive functions, and to assist in spatial orientation (Spenkelink and Besuijen, 1996). Overall, color has the potential to reduce workload and improve visual performance.

The color of monochrome cathode-ray-tubes (CRT) and I^2 displays is defined primarily by the choice of phosphor.[8] And, the choice of phosphor is defined primarily by luminous efficiency. Approaches to achieving color in liquid crystal displays (LCDs) are numerous and increasing every day. One approach is similar to the additive color method employed in modern CRT displays. In this approach, pixels are composed of three or more color subpixels. By activating combinations of these subpixels and controlling the transmission through each, a relatively large color gamut can be achieved. The most promising near-term LCD color technology is subtractive-color. Another display technology, Active Matrix Electroluminescent (AMEL), can provide limited or full color, achieved either by classic filtering techniques of color-by-white or by patterned phosphors similar to those used in conventional CRTs. See Chapter 4, *Visual Helmet-Mounted Displays*, for a discussion of the various display technologies.

A number of studies have expounded on the positive impact of color on performance. In one of the more comprehensive studies, DeMars (1975) concluded that, for certain applications, color enhanced accuracy, decision time, and workload capability. However, Davidoff (1991) and Dudfield (1991) found that the actual significance of color far outweighed its perceived importance. An investigation (Spenkelink and Besuijen, 1996) of whether the use of color, and the resulting available chromatic contrast, could help improve performance in the presence of low luminance contrast concluded that only under special conditions was there an additive effect, and, in general, chromatic contrast cannot be substituted for luminance contrast. Rabin (1996) compared Snellen and vernier acuity, contrast sensitivity, peripheral target detection, and flicker detection for simulated green ($x = 0.331$, $y = 0.618$) and orange ($x = 0.531$, $y = 0.468$) phosphors. For central visual tasks, no differences were found. However, peripheral target detection was found to be enhanced for the green phosphor.

Efforts to develop color HMDs date back at least to the 1970s (Post et al., 1994) at which time Hughes Aircraft under the direction of the U.S. Air Force Armstrong Laboratory, Wright-Patterson AFB, Ohio, produced a monocular display around a miniature, 1-inch, P45 CRT which used a rotating filter to provide field-sequential color. Since this effort, a number of other attempts based on multiple image source technologies and methods have been made with only limited success. However, the most promising approach to providing full color in an HMD is based still on field-sequential color, with its potential field breakup problem.[9] Post, Monnier, and Calhoun (1997) have looked at this problem and developed a model for predicting whether this breakup will be visible for a given set of viewing conditions.

It has been suggested that full color HMDs may not be necessary in some applications, and that, through the use of limited color displays, the cost and complexity of color HMDs may be reduced while maintaining the advantages of color. Reinhart and Post (1996) conducted a study looking at the merits and human factors of two-primary color active matrix liquid crystal displays (AMLCDs) in helmet sighting systems. One of their conclusions was that such a design could prove beneficial in an aviation HMD application.

---

[8] A phosphor is a substance that emits light when struck by electrons or ultra-violet energy. Cathode-ray-tubes (CRTs) are a typical example of display devices that use phosphors.

[9] For sequential color displays, when the observer's eyes move rapidly relative to the display, the R,G, and B images will not fall on the same location on the retina. This can result in color breakup, or perceived spatial separation of the R,G,B components (Zhang and Farrell, 2003).

Besides cost, weight, and complexity drawbacks to the implementation of color HMDs, additional issues are present. The luminous efficiency of the eye is a function of wavelength and adaptation state. For example, at photopic levels of illumination, the eye is most efficient at 555 nm, requiring at other wavelengths more energy to perceive the same brightness. Therefore, it is recommended by some researchers that care must be taken in multiple color display designs to ensure isoluminance (Laycock and Chorley, 1980). Also, it has been found that larger size symbols are required to ensure that both detail and color can be perceived when color is selected over black and white (DeMars, 1975).

The monochromatic displays have produced some problems, with chromatic aftereffects reported with I^2 devices. This problem first was raised in the early 1970s (Glick and Moser, 1974). This afterimage phenomenon was reported by U.S. Army aviators using NVG for night flights. It was initially, and incorrectly, called *brown eye syndrome*. The reported visual problem was that aviators experienced only brown and white color vision for a few minutes following NVG flight. Glick and Moser (1974) investigated this report and concluded that the aviator's eyes were adapting to the monochromatic green output of the NVGs. When such adaptation occurs, two phenomena may be experienced. The first is a *positive* afterimage seen when looking at a dark background; this afterimage will be the same color as the adapting color. The second is a *negative* afterimage seen when a lighter background is viewed. In this case, the afterimage will take on the compliment color, which is brown for the NVG green. The final conclusion was that this phenomenon was a normal physiological response and was not a concern. A later investigation (Moffitt, Rogers, and Cicinelli, 1988) looked at the possible confounding which might occur when aviators must view color cockpit displays intermittently during prolonged NVG use. Their findings suggested degraded identification of green and white colors on such displays, requiring increased luminance levels. Another chromatic issue with display imagery and symbology in see-through HMDs is the effects of the real world background color(s) adding to the display color, resulting in an unintended perceived display color (Wood and Howells, 2007).

Havig et al. (2001) raised an issue with see-through color HMDs in aviation (although the issue will also apply to any see-through HMD application), that of symbol colors summing with the outside scene. They argued that, as a result, the colors may not be sufficiently recognizable due to color mixing, i.e., colors on the display will sum with the colors from outside the cockpit. They further argue that the bright ambient light present during daytime viewing could desaturate colors, e.g., pilots would have trouble discriminating between green and yellow.

Attention Capture

The primary goal of an HMD is to make information available to the user essentially at any time, regardless of the orientation of the user's head. In order to achieve this in a see-through system the display information is superimposed optically on the user's FOV. The user looks through the HMD to view the distal world, which is the physical environment in which the user is functioning and in most instances, interacting. If the user is a pilot controlling an aircraft, the distal world is the airspace and/or terrain through which the vehicle is moving. An important issue to clarify is consequences of superimposing the informational display elements of an HMD on the pilot's view of the world. A first step toward this clarification is to differentiate between the optically superimposed image of the HMD symbols and the distal world whose visual image exists independently of the HMD. One helpful distinction is to refer to the visual elements that are on the HMD as the near-domain (ND) and to refer to the visual elements of the distal world that are independent of the HMD as the far-domain (FD). One might also view through the HMD other displays mounted on a nearby instrument panel inside the cockpit or other objects within arm's reach inside the cockpit.

The motivation behind the strategy of optically superimposing the ND information on the FD is to alter the user's visual search and scanning requirements in order to minimize the amount of time the user needs to look away from the FD to look down and acquire information from inside the cockpit. The superposition of the HMD symbols on the FD enables the user to look through the ND in order to see the FD. Thus, the ND and FD are simultaneously available to the user without a head movement or even an eye movement. This does reduce the requirements for visually scanning between the ND instruments and the FD, but likely will incur some costs vs. performance in each domain separately.

Ocular accommodation

To begin assessing the possible costs, consider accommodation, which is the change of focus of the eye's lens (see Chapter 7, *Visual Function*). The changing focus of the eye is accomplished by the balance of the opposing tensions between the eye's ciliary body and the elastic properties of the lens and its capsule. It is well established in the literature that it takes time for the optical power of the lens to change in order to focus between far and near objects; near objects being those closer than twenty feet. Of course, the magnitude of these accommodation changes is age dependent; but even in a person thirty years old or younger, these changes in accommodation can take a substantial amount of time, as much as a quarter of a second. In order to eliminate these time requirements of accommodation, HMDs are designed to ensure that the ND is at essentially the same optical distance as the FD. This optical technique eliminates the time required to change the focus of the eye between ND to the FD. However, even though the eye need not change its focus when shifting between the ND and FD, the shift in attention between them may not be instantaneous.

Attention switching

Simply because the HMD superimposes the ND on the FD, co-locating them in the user's FOV at the same apparent visual depth, does not guarantee that the user is capable of attending to both the ND and FD at the same time. In fact, just as it takes time for the power of the lens to change, it takes time for attention to change, even though objective or physical measurements of these changes in attention are not as straight forward as the measures of optics of the eye. Furthermore, as discussed below, research shows that the shift of attention is important. For the most part, this research has been conducted with HUDs, e.g., display systems that are not attached to the user's head. Nevertheless, since they superimpose the ND on the FD, it is clearly appropriate to extrapolate from the HUD to the HMD (Yeh et al., 2003; Yeh, Wickens and Seagull, 1998).

These issues were addressed systematically as far back as 25 years ago. The findings of one of the early studies are particularly relevant to the present discussion (Fisher, Haines and Price, 1980). Eight subject pilots flew a fixed-based simulator configured to simulate a Boeing 727-type aircraft. These subjects were all highly trained commercial pilots who flew the Boeing 727-type aircraft for one of two commercial airlines, with thousands of hours of experience. Since, at the time of the study these pilots had little or no previous experience with HUDS, they all received a number hours in HUD training. Almost all of the displayed HUD information was presented graphically in a conformal fashion, e.g., the display "… moved in a one-to-one manner with the real world both in pitch and roll, and that certain elements, such as the runway symbol and the horizon line, were designed to overlay their real-world counterparts" (Fisher, Haines and Price, 1980). The HUD provided an extensive suite of symbols that included pitch, heading, altitude, airspeed, glide slope, flight path, speed error, aircraft reference, localizer, as well as flare information. The HUD instrumentation was designed to be sufficient for a zero-zero[10] landing.

While the study evaluated several flight conditions, one condition is most important for the current discussion; it involved landing with a cloud ceiling of 180 feet (55 meters) and a runway visual range of 2000 feet (610 meters). There was light turbulence, but no cross wind; and, a 150- foot (46-meter) decision height was used. Each simulated test flight began at 1500 feet (457 meters) and 8 miles (13 kilometers) from the runway and lasted approximately 4 minutes. The pilots performed the maneuver with and without a HUD. In order to control for experience effects, half the pilots first flew the maneuver with the HUD, and the other half first flew the maneuver

---

[10] *Zero-zero* is an aviation term used to describe no ceiling (altitude of lowest clouds) and no visibility.

without it. A number of flight parameters were recorded, including whether the pilot landed or executed a missed approach. Video and audio recordings were also made of the pilots.

An additional and important point is that each pilot was exposed to a completely unanticipated event, a runway incursion. As the pilot was coming into the runway, another Boeing-727 was presented halfway onto the runway at a 45° angle, as if it was turning from an adjoining taxiway near the runway threshold. This incursion was completely unannounced and unanticipated. Four of the pilots encountered it for the first time with the HUD; the remaining four encountered it without the HUD. The four pilots who encountered this event with the HUD eventually encountered the same event during a subsequent flight that did not involve the HUD; and, those four pilots who encountered the incursion first without the HUD eventually encountered it during a subsequent flight with the HUD. Although the pilots were not warned that runway incursion would occur again, when it occurred the second time, the pilots were probably not nearly as surprised as they were when it occurred the first time. Of interest is how long it took for the pilots to see the incursion, and when the pilot initiated a missed approach.

Since the incursion was a complete surprise to the pilots only the first time it occurs, there was only one first time for each pilot. So the important results of this study, for our purposes, rests on only eight observations, one per pilot, which was far too few for a statistical analysis. Nonetheless, the results are interesting. Of the four pilots encountering the surprise with the HUD, two of them never saw it. They were landing, looking straight at the runway, and the Boeing-727 sitting there, totally undetected. One pilot said, during the debriefing after viewing the tape of the flight; "If I didn't see it (the tape), I wouldn't believe it. I honestly didn't see anything on that runway" (Fisher, Haines and Price, 1980). The other two pilots did see the incursion and initiated the appropriate missed approach; but these pilots reacted several seconds slower than did the pilots without the HUD.

For the second incursion, the pilots were aware of the possibility of unexpected events. However, each of the four pilots without the HUD initiated the appropriate missed approach more quickly than did the four pilots with the HUD (2, 2, 1, 1 vs. 2, 3, 3, 3 sec.).

About fifteen years later, in a study that partially replicated Fisher, Haines and Price, Wickens and Long (1995) found essentially the same pattern of results. They studied thirty-two pilots landing a flight simulator. The subjects were provided conformal or non-conformal flight instrument suite in either a HUD or head-down display (HDD) configuration. During the last flight of each subject, "… a wide-body jetliner taxied into takeoff position on the runway on which the participant was about to land. … the latency between the time the participants broke out of the clouds and the time at which they initiated a go-around…" was the dependent measure. Again, the subjects were not warned about possible runway incursions; so it was a completely unanticipated event. The results were unambiguous: The participants flying with the HDD responded more quickly to the incursion than did those flying with the HUD; about 6 seconds compared to about 8 seconds, a difference that was statistically significant. Furthermore, there was an interaction effect; the delay was significantly longer with the non-conformal HUD (about 9 sec), that with the conformal one (about 7 sec).

These results should not be taken to suggest that HMD or HUDs are bad by any means. These deficits or negative effects seem to be specific for the detection of unexpected events (Yeh et al., 2003). As far as expected events go, even very low frequency events that the user has been prepared to expect, HUDs, and HMDs seem to support performance as good as if not better than conventional HDD displays. However, the superimposed ND of the HMD and HUDS seem to make detecting the truly unexpected event in the FD more problematic.

It seems fairly obvious that cluttering the FD by superimposing the ND on it should make the FD harder to see simply because there are more things to look at. This general effect of clutter means that the user has more things through which to search for the important specific information (Gish and Staplin, 1995). It also means that more things have to be ignored. There seems to be another more specific crowding effect of clutter, that is, items close to each other interfere with their mutual visibility (Ericksen and Ericksen, 1974). This crowding effect may result from crosstalk among retinal neurons, can extend over substantial regions of the visual field (Westheimer, 2004) and can be exacerbated by increasing stress and/or workload (Larish and Wickens, 1991).

The ND is not a just a scattering of random visual elements cluttering the view of the FD, it is a man-made system of regular geometric shapes and alphanumeric characters designed to convey information. The ND is planned and organized to convey information important for the user. When a pilot uses the ND, rather than merely turning it off, and at least to some extent attends to it and the information it provides, it is obviously not being ignored. This observation introduces another factor that maybe more important than the visual clutter. The symbols and icons of the ND interact with the user's attention in a way that is more compelling that if the symbols were random clutter. This particular factor, that HUDs and HMDs seem to capture a user's attention, emerges from the interaction among the symbols, their informational content, and the characteristics of human attention.

In order to address this second issue, *attention capture*, a few introductory words about human attention may seem appropriate. Attention is often likened to a spotlight that can be directed to specific items of interest. Attention is considered to be a limited cognitive resource that can be allocated in specific ways. The HMD literature has described attention being focused, selective, or divided (Prinzel and Risser, 2004). Focused attention refers to the fact that attention seems to illuminate specific elements in the environment, much the same way that vision is directed to specific elements in the environment. The selective nature of attention refers to the fact that attention, again like vision, seems to go from one element to another in a serial fashion, rather than attending to everything all at once. But even though specific items can be selected for special scrutiny, it is also possible to maintain awareness of more than one thing at a time, thereby dividing attention. Furthermore, it seems that visual attention may be allocated to objects as well as to locations in the visual world. In other words, one attends to an object and to some extent, the space around the object, where the object is located. Usually eye movements play a role in this.[11] But if the HUD and HMD are functioning as designed by optically collocating the ND and FD, the need to make eye movements may be reduced or at least minimized. It is even possible that the user may be able to allocate some fractional attention simultaneously between the ND and FD so that an explicit eye movement may not be necessary. But the shifting of attention between the ND and FD may be more effortful without an eye movement than with one. In other words, the absence of an associated eye movement may even make it more difficult for an individual to shift attention.

Ververs and Wickens (1998) have provided a more formal definition of the phenomenon of attention capture as a "… involuntary (and generally undesirable) fixation of mental resources on an information source, for some length of time, at the expense of other elements. This phenomenon is characterized by the inability to effectively switch (sic) cognitive capacities between sources of information. In the aviation domain, a pilot's attention might become locked on a particular instrument resulting in the failure to scan the rest of the environment. When pilots are flying with a HUD where the instrumentation is superimposed on the far domain scene, pilots may fixate on the centrally located near symbology and ignore important information beyond it in the environment."

They point out that attention capture is a misleading term for several reasons. The word capture implies that it is a one time, all or nothing event, like a trapping or locking up of attention. But it need not be; it may be more like a stumbling or stuttering than an actual capture. Furthermore, ascribing the phenomenon to attention is to ignore the fact that many additional cognitive components such as reasoning, remembering, processing, recognition, response strategy selection and preparation may be involved with the phenomenon. Each of these different cognitive functions may be differentially involved depending on the specifics of the situation. For example, some may involve eye movements and a breakdown of instrument scan patterns while others may not involve eye movements at all. Furthermore, as Ververs and Wickens point out, attention capture is a term that was originally used to describe a different phenomenon that may only be tangentially related to 'attention caption' by the HMD/HUD (Jonides and Ynatis, 1988). In general, the abrupt appearance of an object in a visual display has the capacity to draw attention to itself reliably under a wide variety of stimulus conditions. The compelling nature

---

[11] These eye movements involve the muscles outside the eye that move it to look from place to place and are different from those involved in accommodation, which involve the muscles inside the eye and that control the focusing. [See Chapter 7, *Visual Function*.]

of the transient nature of the stimulus is due to specific processing characteristics of the visual system (Franconeri and Simons, 2005).

Yet the phrase ‘attention capture’ appears intuitively correct since, according to Fisher, Haines and Price (1980), “… several pilots admitted that from time to time they caught themselves totally fixating on the (HUD) symbology, oblivious of anything else, and had to consciously force their attention to the outside scene.” But, both HUD and HMD instruments are designed to be redundant with the FD information. When pilots simultaneously have available both the ND information from the HMD and in the FD, they may simply prefer to use the HMD information. After all, it allows them to control aircraft heading, airspeed, and altitude more precisely than using the FD. Since ND instrumentation provides the pilots with sufficient information, the pilot eventually may become complacent, having little reason to reference the FD. This complacent reliance on the ND contributes to the vulnerability to totally unexpected events. In such situations, it may be reasonable to question how often a pilot does intentionally direct attention from the ND to the FD, and how successful such attempts to shift attention really are. After all, the frequency of such shifts is on a pilot’s own internal schedule that is maintained with no other time-keeping device for self checking. Furthermore, there are such questions as how does the pilot know that the switch of attention from the ND to the FD was successful and is the shift of attention under the pilot’s control.[12] These are purely self monitoring phenomena for which there are no external checks and it has been well established in the ‘attention blindness’ literature that people invariably over estimate their ability to detect changes in their environment. Thus, they are blind to their blindness, which may make them all the more vulnerable (Levin et al., 2000). According to Fisher, Haines and Price (1998), “It is interesting to note that the six pilots who did see the obstacle through the HUD believed (falsely) that they detected it sooner with the HUD than without it. The typical explanation was that ‘The airplane was easier to see with the HUD because I was head-up.”

Foyle, McCann and their colleagues have conducted a series of psychophysical/human performance laboratory studies to examine the ability of individuals to monitor simultaneously the information presented in the ND and in the FD; as well as the time required to shift attention between the two domains (Foyle et al., 1993; McCann et al., 1993; McCann, Foyle and Johnson, 1993; Sanford et al., 1993; Shelden, Foyle and McCann, 1997). In some of these studies individuals also performed a flying-type tracking task that required the individuals to control the heading and altitude of a low-fidelity simulation. Many of these studies used a common overall experimental approach and strategy, with similar equipment, design, and procedures. The ND mimicked the HUD while the FD mimicked the airspace; and both of them were computer-generated graphics presented on an unidentified and unspecified CRT display, presumably a generic desk top unit common at the time.

In a typical study, for example, the HUD image consisted of four small squares; each of which was 1.9 cm (0.75 inch) wide by 1.1 cm wide (0.4 inch). These were arranged in a 2 X 2 pattern, with a horizontal separation of 5.4 cm (2 inches) and a vertical separation of 0.6 cm (0.2 inch). All the HUD information was presented in these four boxes. The HUD also contained a pair of pitch ladders that provided the individual with no task relevant information. The ladders were merely graphical elements whose only purpose seemed to be to define the HUD as a single perceptual object. Other than a passing mention, the pitch ladders were not described in the reports but appeared in the illustration of the stimulus display. Each of the pitch ladders in the illustration consisted of seven horizontal lines arranged in a column that appeared to be about 5 cm (2 inches) high. The two pitch ladders were mirror images of each other, positioned between the boxes, and extending approximately an equal amount above and below the boxes. The HUD was horizontally centered on the CRT, remained stationary throughout each trial, and was blue against the black background.

---

[12] This question is similar to the one raised in the literature on ocular accommodation, which showed that people are notoriously poor at knowing and controlling where their eyes are focusing. Without something to look at, focus goes to a resting point that is remarkably resistant to volitional control.

The FD mimicked an out-the-window view of a runway outlined from an approach perspective. The runway, like the HUD, was a computer generated graphical image comprised of straight lines. In order to create the illusion of depth on the flat screen of the CRT, the runway icon was a trapezoid. The two horizontal lines, conjuring the near and far ends of the runway, respectively, were 1 cm (0.4 inch) and 23 cm (9 inches) at the start of a trial. These horizontal lines were connected by two oblique lines conjuring the sides of the runway, and a third line down the center of the runway icon to conjure the runway centerline. This runway icon was outlined in yellow against the black background of the screen. There was also a dotted horizon line that seemed to be midway on the CRT, extending its full width.

During a trial, the dimensions of the runway icon changed "… making it appear as if the subject was on final approach. In addition, small vertical and lateral displacements were superimposed on the descent (flight path), simulating changes in the aircraft's pitch and yaw. … It took approximately 5 seconds to make contact with the surface of the runway, considerably longer that subjects typically required making their response (McCann, Foyle and Johnson, 1993)." Consequently, in this particular study the subject was not controlling the simulated aircraft, but merely observed a 5-second long computer animation in which the yellow runway icon of yellow straight lines moved against the stationary HUD icon of blue straight lines, both icons against the common black background.

It is worth pointing out that presenting both the ND and FD at the same optical distance on the CRT ensures that the subjects do not need to change to accommodate when sifting vision between the ND and FD, thus eliminating accommodation as a potentially confounding variable.

The task of the individual participating in the experiment was to press one of two keys on a keyboard, selecting one or the other depending on information presented during the trial. The individual's response accuracy and reaction time were recorded. The specific experimental manipulations of this study were the patterns of stimuli presented in the HUD and runway icons. There were three types of stimuli: one type was a cueing stimulus, the second was a discriminative stimulus and the third was a distracting stimulus.

The cueing stimulus could be either the alphanumeric group for visual flight rules (VFR) or the group for instrument flight rules (IFR). At the start of a trial, one of these cues was presented in one of the two lower HUD boxes or on the runway just below but proximal to these lower pair of HUD boxes. The cueing stimulus told the individual whether the next stimulus, which was the discriminative one and which was presented 125 milliseconds (ms) after the cue, would be presented in the HUD or in the runway icon. IFR meant that the discriminative stimulus would be presented on the HUD whereas VFR means that the discriminative stimulus would be presented on the runway. Consequently, if the cue was IFR and appeared on the HUD, then the discriminative stimulus would also appear on the HUD and the subject would not have to shift attention from the HUD to the runway in order to respond to the discriminative stimulus. Similarly, if the cue was VFR and appeared on the runway, then the discriminative stimulus would also appear on the runway and the subject would not have to shift attention from the runway to the HUD in order to respond to the discriminative stimulus. In these two situations, the cue and discriminative stimuli were both presented in the same domains, either in the ND or in the FD. Conversely, if the cue was IFR and appeared on the runway, then the discriminative stimulus would appear on the HUD and the subject would have to shift attention from the runway to the HUD in order to respond to the discriminative stimulus. Similarly, if the cue was VFR and appeared on the HUD, then the discriminative stimulus would appear on the runway and the subject would have to shift attention from the HUD to the runway in order to respond to the discriminative stimulus. In these two situations, the cue and discriminative stimuli were presented in different domains, and the subject had to shift attention between the ND and FD.

The discriminative stimulus was either a stop sign or a diamond and the subject pressed one or the other key depending on whether the stop sign or diamond was the discriminative stimulus. The subjects were told that the stop sign meant that the runway was closed and that the key press initiated a missed approach, whereas the diamond meant that the runway was open and the key press signaled the continuation of the landing. The discriminative stimulus was presented on the HUD or on the runway, in a location unoccupied by the cue.

Simultaneous with the onset of the discriminative stimulus (250 ms after the cue onset) distracting stimuli were presented in the remaining unoccupied boxes on the HUD and the unoccupied locations on the runway. These distracting stimuli were squares and triangles.

The results of this study showed unequivocally that it took longer to shift attention between the HUD and runway than when the cue and discriminative stimuli were both in the HUD or both in the runway. Subsequent experiments suggested that the difference in shifting attention between the HUD and runway depended upon the extent to which these two graphically created icons were distinguished as separate perceptual objects. For example, one of the differences between the HUD and runway was that the runway appeared to move whereas the HUD was stationary. When the study was conducted with a runway that did not appear to be moving, then the difference in shifting attention between the ND and FD was reduced; however, the results contained an important hint. There was little difference in reaction time when both the cue and the discriminative stimuli were both on the (stationary – nonmoving) runway or when the cue was on the runway and the discriminative stimulus was on the HUD. In other words, the subject could just as easily shift attention within the runway or from the runway to the HUD. But; sifting attention from the HUD to the (stationary) runway, took significantly longer than shirting attention within the HUD. Somehow, the HUD icon still seemed to hold attention more strongly than did the runway iconography.

Subsequent elaborations of the basic experimental paradigm required the subjects to fly the low-fidelity simulator. The performance measures were the accuracy (root mean square error) with which the subjects were able to hold assigned altitudes and headings. The experiments manipulated the configurations of the HUD and out-the-window, i.e., the ND and FD views, to identify further the characteristics of attending to these two domains either simultaneously or in succession. The results of these studies agreed with the previous findings. The display of information in the ND interfered with the components of flight performance that were dependent on information from the FD. But, most important, the extent to which the ND affected the subjects' ability to attend to the FD, depended critically on the configuration of the ND. These results suggested to Foyle and his colleagues a strategy that promised to mitigate the perceptual tunneling effects of the HUD, and by extension, the HMD.

This strategy is sometimes referred to as scene-linking and at its core is the notion of reducing as much as possible the perceptual differences between the ND and FD. The ND display components are designed to appear to be part of the FD. For example, the differential motion between the FD and the components of the ND is reduced. The ND components should move with the FD. Sheldon et al. (1997) identified several forms of potentially scene-linking ND symbols "*Scene enhancements* are the graphical outlines of existing objects in the external world, such as a graphic runway that overlays an actual runway, or a virtual horizon. *Scene augmentations* are the addition of virtual, three-dimensional (3-D) objects that are otherwise non-existent in the real worlds, such as 'virtual traffic lights' that may operation on taxiways to separate aircraft. *Virtual instruments* are the depiction of *ownship* flight instrumentation and data such as a glideslope readout on 'virtual billboards' that appear to the side of the aim point of a cleared runway at landing (Sheldon et al., 1997)."

Researchers have realized some of these ideas in the Taxiway-Navigation and Situation Awareness (T-NASA) Cockpit Displays, a system that integrates information from the Differential Global Positioning Satellite system (DGPS), surface radar, and data line to provide graphically on the HUD final approach and cleared taxi route information augmented with a moving map display (Hooey et al., 2000). The T-NASA is one of several cockpit display systems designed to overcome the limitations of the conventional steam gauge-type instruments of the head down instrument panel while meeting the challenges of the HUD and HMD.

Motion Perception

The physical world comprises an ongoing series of spatio-temporal events. The human visual system is sensitive to a limited range of these events. Spatially, some of those events take place among elements that are too small to be resolved by the human visual system (e.g., atoms), and some are too large to be encompassed within the FOV (e.g., galaxies). Temporally, some take place so quickly that they escape our notice (e.g., the flight of a bullet), and some, so slowly, that they appear static during a given observation interval (e.g., a plant growing). Real-world events, which involve continuous changes of position over time and which fall within certain spatio-temporal boundaries, give rise to perceptual experiences that are called *real* motion (Goldstein, 2007). Real motion percepts belong to the more general class of *visual motion* percepts that include *apparent* motion (Anstis, 1978), *induced* motion or motion contrast (Nawrot and Sekuler, 1990), and motion *aftereffects* (MSEs) (Mather, Verstraten and Anstis, 1998). The additional classes of motion percepts are demonstrations that continuous motion is not necessary for the experience of visual motion.

The goal of this section is to describe the basic phenomena of visual motion and their underlying mechanisms, with limited references to (implications for) the design of visual displays. After an initial review of the spatio-temporal characteristics of the overall visual system, the section proceeds sequentially from the most basic building block of visual motion, the directionally selective cell (modeled as a local, first-order, motion-energy detector for luminance-defined inputs), to more complex processing of motion events (various forms of apparent motion, induced motion, MAEs, temporal motion priming, structure-from-motion, biological motion, optic flow, ego motion) mediated by the spatial and temporal integration of local motion signals and their inputs to higher motion processing stages. The section on visual motion with luminance-defined inputs is followed by a major discussion of the variety of non-luminance stimulus dimensions that support motion percepts, along with the second-order motion mechanisms that underlie them. The section is written at a higher level than an introductory text, so it presumes some familiarity with concepts like the retina, receptive fields, psychophysics, frequency analysis, and filter concepts. The visual phenomena and mechanisms included in the section are chosen primarily for their ability to contribute to an organized understanding of visual motion in general and only secondarily for their contributions to display/HMD design. Certainly, not all display/HMD implications are discussed explicitly (nor could they be in limited space), but a few are included in the text in the appropriate locations (e.g., refresh rates for displays, breaking of camouflage by motion, ego motion, and input saliency). The section is *not* intended to be a comprehensive review of existing applied research on display/HMD design based upon vision/cognition principles. Moreover, the section does not address issues related to optic flow and ego motion when they involve the processing of non-visual motion information. Its scope would have to be expanded significantly to include cues from other sensory systems (e.g., tactual, proprioceptive, vestibular) and even elements of cognitive interpretation of multi-modality information. The limitations engendered by not addressing non-visual cues in motion perception is illustrated by a study (Schulte-Pelkum, Riecke and von der Hyde, 2003) that obtained differences in the degree of ego motion (perception of self motion) generated by a visual stimulus displayed on a projection screen and on an HMD. Ego motion was significantly less with the HMD, with which, when compared to a projection screen, an observer is in tactual contact and which moves when an observer moves. Non-visual cues on motion perception notwithstanding, the analysis of the relationship between visual information and motion perception and the mechanisms underlying the relationship cannot be over-estimated.

Historically, one could easily argue that the modern, scientific approach to understanding visual motion began with the study of *apparent* motion. If two stationary stimuli are presented a short distance apart in rapid succession, humans report an *apparent* motion of a single stimulus between the two positions of the stimuli, even though no physical motion actually occurs between them. Perhaps because the discrete display can be considered the minimum for specifying motion physically, it has been exploited as one way to analyze and characterize visual motion sensitivity in general (Anstis, 1978). Exner (1875) used electrical sparks as stimuli and found that, when two sparks were too close to be resolved spatially, they could nonetheless give rise to a perception of motion when presented sequentially. Exner concluded that apparent motion could not be inferred from a change of position over time, but must be a primary perception on its own.

Spurred on by Exner's observations, other researchers have pursued apparent motion for both theoretical and practical reasons. For the Gestalt psychologist Wertheimer (1912; cited in Palmer, 1999), apparent motion constituted an example of an emergent property whose nature was explored by varying the timing of and spacing between discretely displayed elements. Korte (1915; cited in Palmer, 1999) extended the analysis further and developed a set of descriptive laws relating the perception of motion to three parameters of apparent motion displays: stimulus timing, spacing and intensity. One major limitation of the early studies was their reliance on subjective reports of the presence or absence of apparent motion, or reports of its quality. A second limitation was the implicit assumption that the empirical relationships they discovered were a description of one, more or less, homogeneous motion system. With more advanced psychophysical techniques, recent studies of apparent motion have provided results which contribute substantially to theories of multiple motion processing mechanisms (more detail below) and to data valuable for the practical design of imaging systems.

Spatio-temporal range of the overall visual motion processing system

Happ and Pantle (1987) used *d'* (Green and Swets, 1966) as an objective measure of directional motion and required observers to discriminate the temporal order of onset (stimulus onset asynchrony [SOA]) of two side-by-side light-emitting diodes. They found that *d'* was an approximately linear and increasing function of log(SOA). For foveal vision, the SOA's were smallest for spatially abutting diodes (0° separation), and sensitivity to differences of onset order as small as 1.6 msec were discriminable at above-chance levels. For peripheral vision, SOA's were smallest with a spatial separation of approximately 1° of visual angle. Again, SOA's in the neighborhood of 1 to 2 msec were sufficient for directional judgments at above-chance levels. The results demonstrate that directional judgments are possible at presentation rates that are an order of magnitude faster than refresh rates commonly used for television and computer displays (~16 msec).

Other researchers have used frequency analysis to characterize the overall spatio-temporal performance of the visual system with luminance-defined stimuli. Using flickering gratings produced by spatial and temporal modulations of the luminance of a display, Robson (1966) and van Nes et al. (1967) measured the minimum contrast required for an observer to detect a grating as a function of its spatial and temporal frequencies. In both studies an interaction between spatial and temporal frequency was obtained. Spatial (temporal) contrast sensitivity behaved like a low-pass filter for high temporal (spatial) frequencies, but like a band-pass filter at low temporal (spatial) frequencies. More importantly here, it was demonstrated that the high spatial and temporal frequency cutoffs of the contrast sensitivity functions were relatively independent of one another. The cutoffs describe frequency limits above which contrast variations are not visible, no matter how high their contrast.

It is possible to use the high spatio-temporal frequency cutoffs to construct a window of visibility for contrast variations (Watson, Ahumada and Farrell, 1986), with spatial frequency along one (vertical) side of the rectangular window and temporal frequency along the other (horizontal) side. Visible spatial and temporal frequencies of luminance modulation would be represented by points within the window, with invisible ones falling outside. With such a window, it would be predicted that the perception of a time-sampled display of a continuously moving stimulus would not be changed as long as the sampling introduced frequency components that lie only outside the window of visibility. Measurements of the ability of human observers to discriminate between apparent (time-sampled) and real motion displays confirmed predictions derived from the window of visibility. In general, critical temporal sampling frequencies below which apparent and real motion appeared identical increased with stimulus velocity as predicted. Temporal sampling frequencies in the 200 to 300 Hz range were required for a line moving at 15°/sec to appear identical to a continuously moving line. These results, like those on temporal order judgments, indicate that modern display devices with refresh rates of 60 to 120 Hz may act as temporal filters of environmental information potentially useful to human observers.

Motion processing with luminance-defined stimuli: First-order motion mechanisms

Part of the basis for concluding that visual motion is a primary sensation in its own right can be found in the directionally selective (DS) mechanisms of the visual system. DS elements compare the changing distributions of luminance within local neighboring regions of the retina. Their ability to respond selectively to direction of motion derives from two anti-symmetric inputs (from sub-units) with different time courses. Direction-sensitive neurons have been found in many species, and their operation has been described extensively for the fly (Reichardt, 1961), the rabbit retina (Barlow and Hill, 1963), and the visual cortex of cats and monkeys (Hubel and Wiesel, 1962, 1968; Rodman and Albright, 1987). The existence of DS mechanisms in humans was first demonstrated by Sekuler and Ganz (1963) in psychophysical experiments. After prolonged adaptation to a grating moving in one direction, the threshold contrast required to detect a grating moving in the same direction was higher than that for a grating moving in the opposite direction.

Besides the direction-specific threshold elevations found by Sekuler and Ganz (1963), other psychophysical results have been interpreted as support for the existence of DS elements which are selectively sensitive to the direction of motion of luminance-defined stimuli. The contrast threshold for a sine-wave grating moving in one direction is not changed when it is superimposed upon a sine-wave grating moving in the opposite direction (Sekuler, Pantle and Levinson, 1978). When added together physically, the contrasts of the two gratings do not sum visually to make the result (a flickering counter-phase grating) any more visible than either directional component viewed alone.

After fixating a pattern moving in a uniform direction for a period of time, a stationary pattern will appear to move in the opposite direction, the so-called MAEs. According to Sekuler and Pantle (1967), the moving pattern is hypothesized to selectively adapt DS elements for one direction of motion and leave elements sensitive to the opposite direction unaffected. The resulting imbalance provides a signal for the stationary pattern to move in the opposite direction. Because the population of DS elements is assumed to comprise units with different spatio-temporal response characteristics, adaptation to a moving pattern would be predicted to be velocity-specific, as well as direction-specific. It is not surprising then that adaptation to a moving grating has been found to elevate the contrast threshold for a test grating moving at a similar velocity, but not those for test gratings moving appreciably slower or faster (Pantle and Sekuler, 1968).

Computational models, based upon the physiological properties of DS neurons, have been developed by a number of researchers (Adelson and Bergen, 1985; Marr and Ullman, 1981; van Santen and Sperling, 1984, 1985; Watson and Ahumada, 1985) to simulate local motion detectors in humans. While the algorithms employed in the different models differ in detail, in each case the inputs to a DS unit are modeled with a pair of sub-units (filters) with spatial weighting functions (receptive fields) in an approximate quadrature phase. In addition, the inputs of the sub-units to the DS element are temporally offset or filtered to produce appropriate time courses of action on the DS element. An array of DS units with different spatio-temporal characteristics is assumed to service each local region of the retina and to produce a crude, local Fourier analysis of a given input stimulus. As a class, the models are called motion-energy models, and the spatio-temporal luminance distribution in a local region of the retina is defined as their input. For this reason, they are also said to generate first-order motion signals in contrast to motion mechanisms (second-order) which take contrast, texture, depth or motion differences as their input [presented in more detail later (Smith, 1994)]. The hypothesis which links outputs of the motion-energy class of models with the perception of motion by human observers is the *motion-from-Fourier-components principle* (Chubb and Sperling, 1988). The motion percept elicited by a complex stimulus will be in the direction of the spatio-temporal frequency components with the greatest expected power. If the expected power in any one direction is matched by the expected power in the opposite direction, the stimulus is said to be *drift-balanced*, and no motion will be perceived. The first-order motion models have been used to explain, simulate and predict the results of human psychophysical experiments with simple and complex luminance-defined stimulus patterns. A few empirical results obtained with specially constructed stimuli demonstrate the usefulness of the motion-energy model.

Observers report that a square-wave grating which jumps ¼-cycle to the right will appear to move rightward. However, the same grating with its fundamental spatial frequency (Fourier) component removed will appear to move leftward (Adelson and Bergen, 1985). This result is explained by the motion-energy model in the following way. A square-wave grating is made up of a fundamental sine-wave component along with odd harmonics of the fundamental whose amplitude decreases in proportion to their frequency. For a square-wave grating, the fundamental and every other spatial frequency component (1f, 5f, 9f, etc.) shift ¼-cycle to the right with each jump and contain more average rightward power than the average leftward power of the remaining components (3f, 7f, 11f, etc.) which shift ¾-cycle to the right (¼-cycle to the left) with each jump. For a missing fundamental grating, there is more average leftward power than rightward power. For each rightward shifting component (5f, 9f, 13f, etc.) there is a leftward shifting component with greater power (3f, 7f, 11f, etc.).

If two identical pictures are presented sequentially in overlapping but slightly displaced positions, motion will be perceived in the direction of the physical displacement as expected in normal apparent motion. If, however, the second picture is a contrast-reversed (negative) version of the first picture, then surprisingly motion will be perceived in a direction opposite the physical displacement (Adelson and Bergen, 1985; Anstis, 1970; Anstis and Rogers, 1975). The reversal of apparent motion is consistent with the motion-from-Fourier-components principle of the motion-energy model. The control exercised by a number of other variables on forward and reversed motion in two-frame, apparent motion displays are simulated with computational models based upon motion-energy detectors (Pantle and Turano, 1992; Strout, Pantle and Mills, 1994).

Lastly, consider a compound stimulus which results from the linear superposition of a drifting sine-wave grating (motion stimulus) and a stationary sine-wave grating of the same spatial frequency (called a pedestal) (van Santen and Sperling, 1984). The compound stimulus contains luminance peaks which merely oscillate back and forth and do not provide any non-equivocal information about direction of motion to a system designed to track features. On the one hand then, it is somewhat surprising that human observers' reports are not only directional, but also virtually identical when the moving sine-wave grating is shown alone or superimposed on the stationary pedestal. On the other hand, a first-order motion-energy system possesses the property of *pseudo-linearity* whereby its response to the compound stimulus is simply the sum of its responses to the individual sine-wave components. As a corollary, the addition of the stationary pedestal grating with a temporal frequency of zero would produce a zero output from a motion-energy system and would not disturb its non-zero response to the moving component grating.

Comparisons of the putative motion-energy detectors in humans with their physiological correlates in other mammals and primates makes it likely that they are located at early stages of visual processing (V1 of the striate cortex) (Emerson, Bergen and Adelson, 1992; Movshon and Newsome, 1996). Hypothetical interactions between the motion-energy detectors and further processing of their outputs by higher-level mechanisms have been offered as the basis of other visual motion phenomena (Simoncelli and Heeger, 1998). A few examples are described in more detail here -- motion priming, structure-from-motion, motion contrast and assimilation, biological motion, and self-motion.

The perceived motion of a vertical sine-wave grating which undergoes an abrupt 180°-phase shift (motion step) is ambiguous. The grating sometimes appears to move rightward; sometimes, leftward. In a system of motion-energy detectors the output of rightward and leftward detectors would be expected to be balanced, but in any one instance "internal noise" would favor one or the other direction. When the ambiguous, 180°-step follows closely upon an unambiguous step (e.g., 90°) which would activate only motion-energy detectors for one direction, the perceived direction of the ambiguous step is biased in the direction of the unambiguous step (Pinkus and Pantle, 1997). The bias is termed visual motion priming and lasts approximately a second. The biasing can be explained by a persistence of the directional response of motion-energy detectors to the priming motion and its temporal integration with the balanced response of motion-energy detectors to a 180°-step. Variations on the priming paradigm support the temporal integration explanation. Visual motion priming demonstrates the benefits of multi-frame representations of directional motion over the minimum two-frame representation (Snowden and Braddick, 1989).

Perhaps the simplest example of spatial interactions generated by local motion-energy detectors is the formation of a *structure-from-motion* with random-dot kinematograms (RDKs). RDKs are motion displays typically consisting of two frames of random black and white dots presented in alternation. In one version of an

RDK, one rectangular region in both frames contained identical elements and is shifted slightly from one frame to the next. The remaining portion of each frame contains independently generated black and white dots; they are therefore uncorrelated across frames. Viewed alone each frame looks only like a pattern of random dots. When animated however, the coherently displaced subset of random dots emerges as an organized structure, a rectangular figure against a noisy background (Braddick, 1974). A simple pooling of local motion-energy signals generated by the coherent global displacement of the dots in the rectangle in the absence of any consistent directional signal in the surrounding area could be the physiological process underlying the perceived structure. If indeed local motion signals are necessary for the emergence of the perceived structure, then spatial displacements of the rectangular region which are large and fail to activate the local motion-energy detectors will cause the motion-generated structure to disappear. Similarly, if the time between the two frames is made too long, no structure-from-motion will be seen. Initially, the spatial limit (D_{max}) obtained by experimentation was approximately 1/4° of visual angle, and the temporal limit (T_{max}) was approximately 80 ms (Braddick, 1974). The underlying substrate responsible for the emergence of the structure-from-motion was termed the short-range process by Braddick (1974). Since Braddick's early research, new experiments (for a review, see McKee and Watamaniuk, 1994) have found that D_{max} and T_{max} are not absolute limits, but can vary with stimulus conditions and stimulus filtering. In the real world, structure-from-motion mediated by first-order motion detectors is one of the most potent factors in the breaking of camouflage and the attraction of visual attention to an otherwise hidden object.

Spatial interactions among first-order motion signals have been shown to be more complex than excitatory summation or facilitatory pooling across common motions in time or space. Nawrot and Sekuler (1990) used RDKs in which dots in alternating (spatial) strips tended to move uniformly in one direction or in random directions (dynamic noise). When the alternating strips were narrow, the strips with uniform motion induced a common motion in the noise strips (motion assimilation); when they were wide, the strips with uniform motion induced a motion of the opposite direction in the noise strips (motion contrast). Motion contrast has been explained by inhibitory interactions between motion-energy units (Murakami and Shimojo, 1996). The motion-energy units activated by a directional stimulus are assumed to upset the balance (a zero net response) of motion-energy units that response equally (or not at all) to a stationary stimulus.

Even more complex are the point-light displays which give rise to biological motion. Johansson (1973) filmed an actor in the dark with small lights attached to his joints (shoulders, elbows, wrists, hips, knees and ankles) so that nothing was visible except the lights. When the actor was stationary, observers perceived only a meaningless pattern of lights. When the actor moved, observers reported that they saw a person moving within fractions of a second. The biological motion percept requires the integration of signals for motions in different directions and velocities. Like the motion of a single point, biological motion appears to be a primary sensation in its own right, and single neurons have been found in higher stages of the visual system (superior temporal sulcus, STS) which respond selectively to biological motion (Oram and Perrett, 1994).

The instantaneous motion of elements (optic flow pattern) portrayed on the retina of an observer as (s)he moves about can be represented by a vector field. For example, when a person moves forward toward an object, the vector field would consist of vectors of different directions and lengths pointing outward (optical expansion); when moving backward, a pattern pointing inward (optical contraction). It has been suggested that a mechanism which combines the motion vectors would provide information about the direction in which an observer is headed (Blake and Sekuler, 2006). Regan and Beverley (1978) have shown that it is possible to selectively adapt the human visual system to optical expansion and contraction providing evidence for the existence of cells which explicitly encode expansion and contraction patterns. The existence of such cells has been confirmed in studies of single neurons of area of the medial superior temporal area pars dorsalis (MSTd) in the primate cortex by Tanaka and Saito (1989). Interestingly, those MSTd cells have extremely large receptive fields, likely a reflection of each neuron's input from many motion-energy detectors at earlier stages of the primate visual system. When patterns of optical expansion and contraction are displayed in a virtual environment, an observer experiences self-motion even though they are stationary.

In conclusion, luminance-defined stimuli are thought to generate elementary, low-level, motion signals in so-called first-order, motion-energy detectors. The elementary sensations are elaborated into more complex motion experiences through the interaction and combination of the elementary signals at later stages in the visual system. Both elementary and some complex motion experiences appear to be primary sensations in their own right.

Motion processing with non-luminance defined stimuli: Second-order motion mechanisms

The spatial (D_{max}) and temporal limits (T_{max}) for the perception of motion in RDKs (discussed earlier) are markedly shorter than what has been found with classical studies of apparent motion (large objects on a uniform background). Assuming that the RDK limits are properties of an early-stage, low-level system of motion-energy units, some other system was assumed to be responsible for the apparent motion in the classical studies. This second mechanism was called the long-range motion system by Braddick (1974), but see also Petersik (1989) and Cavanagh and Mather (1989) for further viewpoints on the nature of the short- and long-range motion systems.

Visual bistable figures are stimuli that produce perceptions which oscillate over time. One classical static example is the Necker cube. The element-group movement display is another example of a dynamic bistable stimulus (Pantle and Picciano, 1976). The motion display contains two frames with three equally spaced dots (elements) in each frame on a homogeneous background. The dots in one frame are displaced back and forth between frames by the distance between the dots, such that the center and rightmost dots in one frame overlap the leftmost and center dots of the second frame. When the time between frames is of the order of 10's of milliseconds, the animation is bistable. Observers alternately report a perception in which all three dots appear to shift together by the same amount (group motion) and a perception in which the overlapping dots remain stationary and the remaining dot appears to flicker or shift from one end of the display to the other (element motion). Attneave (1971) explained bistable phenomena in general by proposing that they were analogous to an astable multi-vibrator electronic circuit which alternated between two states and was the result of two interacting semiconductors. Borrowing upon the multi-vibrator model, Pantle and Picciano (1976) explained element-group movement bistability in terms of two competing motion mechanisms. Further research (Petersik and Pantle, 1979) demonstrated that one or the other of the competing movement perceptions could be favored by the manipulation of stimulus conditions. However, those conditions which favored group movement were not like those of first-order, motion-energy detectors.

As it became clear that not all motion percepts were mediated directly by first-order motion-energy detectors, researchers sought to specifically develop displays which would elicit motion percepts, but which were not based upon luminance-defined stimuli. Pantle (1973) reported that human observers experienced apparent motion with a stimulus not defined by luminance. Each frame of a two-frame apparent motion sequence contained a rectangular area with randomly positioned line segments, all with the same orientation, on a background of randomly positioned line segments whose orientation differed from that in the rectangular area by 90°. The position of the rectangular area was shifted laterally across frames. When the two frames were temporally alternated, observers saw the line segments in the rectangular area move back and forth as a group across the line segments in the background (texture motion). The global movement of the rectangular group of elements was seen despite the fact that the rectangular area was not defined by luminance; the rectangular area had the same average luminance as that of the background. What is most significant about this finding is the fact that the perceived texture motion could not have been mediated by first-order motion-energy units which require luminance-defined inputs. Besides orientation differences, other non-luminance differences have been studied extensively to determine whether or not they have the ability to define stimuli (second-order stimuli) which support motion percepts. The goal of the research has been (1) to investigate the variety of non-luminance defined stimuli that support motion processing, (2) to determine what type of non-linear transformations of stimulus luminance might make a second-order stimulus amenable to motion-energy computations, and (3) to study and compare the response characteristics of first- and second-order motion processing.

The variety of non-luminance defined stimuli which support motion perception is large. They include both non-periodic and periodic stimuli. An amplitude-modulated (contrast-modulated) grating is one whose spatial contrast varies periodically across the pattern. It is the product of a high spatial frequency sine-wave (carrier) and a lower spatial frequency modulating waveform. If the modulating waveform is itself a sine wave, then the resulting complex wave can be analyzed as the sum of a fundamental frequency and two sideband frequencies. If the modulating waveform moves, and the carrier is stationary, the two sideband components move in opposite directions. First-order motion-energy detectors would signal no motion and would not support a motion percept because the net directional energy would be zero according to the motion-from-Fourier components principle. Yet, human observers do see the motion of the contrast variations of the amplitude-modulated grating (Pantle and Turano, 1992). The motion would be revealed to motion-energy detectors, if a point-wise transformation like rectification were first applied to the grating stimulus. The second-order contrast variations would be transformed to intensity variations which would be visible by motion-energy detectors.

A slightly more complicated stimulus transformation prior to motion processing could reveal the motion of the orientation-defined figure in the example described earlier. The application of a spatially oriented filter followed by the application of a grossly non-linear point-wise transform would produce an intensity-defined output capable of activating motion-energy detectors. Even more stringent principles can be followed to guarantee more strongly that the motion of any second-order stimulus is not due to activation of first-order motion detectors. Chubb and Sperling (1988) created second-order stimuli, which they defined as drift-balanced. The expected energy of any Fourier component of a drift-balanced stimulus is equal to the expected energy of the component of the same spatial frequency drifting at the same rate in the opposite direction. Following this maxim guarantees that the response of all first-order motion detectors, no matter what their spatio-temporal frequency tuning, would be balanced for opposite directions of motion, not just the response expected across all detectors as a group. One example of a drift-balanced stimulus is a flicker grating, which is the result of the modulation of the flicker frequency of spatial noise (a random array of black and white pixels) with a drifting sinusoid. The motion of the flicker-defined grating is invisible to first-order motion-energy detectors, but nonetheless observers perceive its motion. The motion can be revealed by second-order motion-energy computations applied to the rectified output from an earlier temporal filtering stage.

In conclusion, it is clear on the one hand, that human motion perception is not mediated solely by first-order motion-energy detectors which operate directly on the raw spatio-temporal luminance distribution of an image, as is demonstrated by the sheer number and variety of non-luminance defined stimuli which induce some motion percepts. On the other hand, computational findings demonstrate that motion-energy detectors are capable of signaling motion with second-order stimuli provided only that the stimuli are first subjected to suitable filtering followed by a non-linear transformation. Moreover, more analytical experiments with specially constructed second-order stimuli show that visual phenomena analogous to reverse motion and pedestal immunity which are signatures of first-order, motion-energy processing also obtain for second-order motion processing (Chubb and Sperling, 1988). Findings of the immobility of second-order motion in the periphery notwithstanding (McCarthy, Pantle and Pinkus, 1994; Pantle, A., 1992), properties of first- and second-order motion processing have been found to be remarkably similar (Lu and Sperling, 2001). Despite the demonstrated explanatory power of motion-energy computations for first- and second-order stimuli, there are some remaining visual motion phenomena which cannot be explained by such mechanisms. For example, animated apparent motion sequences in which frames are alternately presented to the right and left eye are capable of creating vivid impressions of motion, yet it is known that motion-energy computations are strictly monocular. Interocular motion provides hints of a third human visual motion system (Lu and Sperling, 2001). The search for physiological substrates of motion processing, no matter what the final outcome of psychophysical research and computational modeling, shows that motion processing takes place in channels or pathways that are segregated from form (object) processing.

Motion processing: Physiological substrates

It is generally accepted that the primate visual system comprises two partially independent, parallel pathways defined by the input attributes (dimensions) which they are optimized to analyze. The division is based upon physiological research on primates, and neurological and psychophysical studies on humans (Lennie, 1980; Livingstone and Hubel, 1988; Merigan and Maunsell, 1993). Alternative names (what/where, dorsal/ventral streams) have been used to refer to the two pathways (subsystems), but here, we will follow the lead of those who have named them the parvocellular (P) and magnocellular (M) pathways, based on the dichotomy of the cell body sizes predominant in each system. The P-pathway extends from P-cells in the retina to structures in the temporal lobe; the M-pathway, from M-cells in the retina to structures in the parietal lobe [MT (V5) and MST]. Single-cell recording of P- and M-cell activity show that P-cells code color differences whereas M-cells do not. P-cells have a greater spatial acuity (higher spatial frequency cutoff) than M-cells. P-cells respond less well to temporal fluctuations of stimulus intensity (have a lower temporal frequency cutoff) than M-cells. Finally, transmission of signals is slower in P-cells than in M-cells. Given the functional differences between P- and M-cells, it is not surprising that lesions in the P-pathway produce deficits in color vision, texture/form perception, and spatial acuity, whereas lesions in the M-pathway produce deficits in flicker and motion perception (Merigan and Maunsell, 1993). The difference of behavioral functions ascribed to the P- and M-pathways can be exploited in display/HMD design. On the one hand, for a dynamic display primarily intended to portray motion, there would be no advantage to color coding or maximizing spatial resolution. Fast refresh rates as outlined earlier in the section would be desirable. On the other hand, for a static display primarily intended for detailed object recognition, fast refresh rates would be superfluous, whereas color coding and high spatial resolution would be beneficial.

More detailed analyses of the MT-pathway with lesions, single-cell recordings, cell micro-stimulation, and functional magnetic resonance imaging *(*fMRIs) have provided data that demonstrate even more strongly the connection between the M-pathway and the results of psychophysical and computational studies of visual motion. They also show a correlation between M-pathway response characteristics and saliency/eye fixations. A number of researchers have noted the similarities between motion-energy detectors in computational models used to explain first-order motion phenomena and single DS cells in cortical V1. Emerson, Bergen and Adelson (1992) made extensive measurements of 1- and 2-bar test responses of DS complex cells of V1 in the cat. The single-bar responses and 2-bar interactions yield highly distinctive patterns, and they matched the predicted responses of first-order, motion-energy detectors quite well.

The input of DS cells to MT (V5) and MSTd single cells at higher stages in the M-pathway allows for the combination of the outputs of first-order motion-energy detectors needed to explain various grouping phenomena observed behaviorally in monkeys and humans. One particularly useful stimulus contains a set of randomly positioned dots, a fraction of which are made to move in a common direction (percent motion coherence). Across trials, the percent coherence is varied. Using the coherence stimulus, Newsome, Britten and Movshon (1989) found that, as the dots' coherence increased, an MT neuron's firing rate increased, and a monkey judged the direction of movement more accurately. At a coherence value in the neighborhood of 12.8%, the MT neuron fired significantly greater than baseline, and motion was judged correctly on virtually all trials. Lesions of MT cortex reduce the number of correct judgments of dot direction (Newsome and Pare, 1988), and micro-stimulation of a column of *DS* MT cells during an experimental trial leads a monkey to shift its judgment in the direction of the stimulated cells (Movshon and Newsome, 1992). Single-cell responses to optic flow patterns (expansion/contraction or rotation) which produce induced self-motion in humans have been found in the MSTd area of the monkey cortex. Tanaka, Fukada and Saito (1989) proposed a scheme to explain the obtained preferences of MSTd cells for specific patterns of optic flow. Each MSTd cell was hypothesized to receive inputs from a number of MT cells with appropriate direction tuning and receptive field location.

Neurological studies of brain lesion deficits in humans reinforce psychophysical and computational studies which propose separate, specialized detectors for second-order motion. In clinical studies, one patient suffered brain damage which impaired perception of motion with first-order stimuli, but not second-order stimuli; a second patient with different brain damage had impaired second-order motion, but not first-order motion (Vaina, Cowey and Kennedy, 1999). In a thorough fMRI study Smith et al. (1998) examined activity levels produced by first-order motion and three types of second-order motion in seven different areas of the human visual cortex. Area V5 was found to be strongly activated by second-order as well as by first-order motion. Activity in Area V3 and VP was significantly greater for second-order motion than for first-order motion. The results are consistent with the hypotheses that first-order motion sensitivity arises in V1, that second-order motion is first represented explicitly in V3 and VP, and that V5 is involved in further processing of motion information, including the integration of motion signals of the two types. It should be noted that the hypotheses are in agreement with the findings from single-cell and neurological studies cited above on the M-pathway, but the conclusions about the exact physiological substrates of first- and second-order motion in humans should still be regarded as tentative.

The relationship between the M-pathway and attention is an important one for guiding behavior. The search for a target in a complex natural scene is generally a serial one in which saccadic eye movements and attention are directed successively to different salient areas (Parkhurst, Law and Niebur, 2002). Salient target areas are processed more completely and quickly than non-salient areas. Among other variables, first-order stimulus cues such as intensity or luminance contrast have been shown to contribute significantly to saliency. Second-order stimulus features, like orientation or texture contrast, are less effective in demarcating salient areas. Furthermore, a number of studies suggest that eye movements and the deployment of visual attention to salient areas defined by first-order stimulus cues are mediated by the M-pathway (Cheng, Eysel and Vidyasagar, 2004; Parkhurst, Law and Niebur, 2002; Steinman, Steinman and Lehmkuhle, 1997). Static second-order or isoluminant color cues, which activate the P-pathway alone, are less effective in signaling salient areas. It is not surprising then that stimuli which are designed to activate the M-pathway dominate visual processing when put in competition with stimuli which activate the P-pathway alone (Steinman, Steinman and Lehmkuhle, 1997) or that they produce faster response times in a search task (Cheng, Eysel and Vidyasagar, 2004). As a consequence, displays/MHD's that highlight potential targets with flickering or moving markers would be more effective than those which employ markers based upon other visual dimensions (e.g., color) (Pinkus, Poteet and Pantle, 2008).

A review and thoughtful analysis of the many types of visual motion phenomena makes it clear that visual motion is not a simple perception mediated by a single, unitary mechanism or process. It is a complex perceptual dimension elaborated in a specialized pathway, which itself contains sub-pathways and multiple stages of analysis.

Monocular vs. Binocular Vision

The use of HMD systems is more prevalent in today's complex operational environment to increase Warfighters' situational awareness, command and control, survivability, and mobility. The dismounted Warfighter must maintain situation awareness—both globally and locally—during operational tasks such as land navigation, target identification and location and usually must do all this while moving within a complex operational environment of coarse terrain and adverse climates. Hence, HMDs provide Warfighters with visual enhancement in conditions where the unaided eye would be less than an optimal tool. HMDs display symbology or imagery to either one eye (i.e., monocular HMDs) or both eyes (i.e., binocular/biocular HMDs) by the way of imaging sensor systems—e.g., image intensification (I^2) and forward-looking infrared (FLIR)—that have been incorporated into military aircraft and mounted vehicles.

Despite the potential visual and operational advantages of HMDs, there can be problems with their use. For instance, a number of studies have documented complications such as eye and oculomotor strain, dizziness, nausea, headache, disorientation, visual illusion and visual distortion (Kooi, 1986; Rash and Hiatt, 2005; Rash et al., 2001; Wenzel, 2002). These problems are likely to be induced by the unnatural viewing conditions of HMDs.

Large differences exist between naturally perceived vision (e.g., cues of depth and true stereopsis) and the monocular or binocular/biocular vision obtained through HMDs. These problems may account for some reduction in visual performance while wearing HMDs such as decline of distance judgment, response time delay and target identification (Arditi, 1986; Conticelli and Fujiwara, 1964; Ginsburg and Easterly, 1983). Consequently, there are a number of visual perception trade-offs that must be considered during a 'human-centered' approach toward HMD selection (i.e., monocular vs. binocular/biocular) and design process (Leger, 1994).

Monocular viewing

Monocular HMDs have the advantage of being smaller, lighter weight, and lower cost than binocular designs. Monocular presentation also allows one eye always to be available for viewing cockpit instrumentation or for dark adaptation. However, two major concerns are associated with monocular HMDs: *binocular rivalry* and *suppression*. When wearing a monocular HMD, the optical input to the two eyes differs greatly; thus creating potential interocular differences in color, contrast, brightness, shape, size, motion, and accommodation demand (Patterson, 2006; Velger, 1998). In fact, visual problems associated with monocular visual stimulation by the Apache IHADSS have been reported during both combat and non-combat missions (Crowley, 1992; Rash and Hiatt, 2005; Rash et al., 2001). Among the most common reported complaints are: degraded visual cues, visual illusions (static and dynamic), and visual discomfort.

Depending on the type of monocular HMD, one eye views the symbology of the HMD while both eyes view the real world scene. Alternately, with other monocular HMDs such as the IHADDS, one eye (i.e., right) views the displayed symbology while the other eye (i.e., left) views the external real world scene or the cockpit displays. This perceptual condition is referred to as dichoptic viewing, which can induce binocular rivalry—the alternation of perceived images that results when different visual images are presented to the two eyes and cannot be fused into a single percept. Binocular rivalry usually is resolved by suppressing the visual input unilaterally, and the attention may alternate spontaneously between the views received from each eye (Patterson, 2006). However, suppression can further reduce the visibility of the background or the monocular symbology. Furthermore, such dichoptic viewing, under sustained periods of monocular viewing and suppression, places great demands on the visual system and may be expected to result in high workload and stress levels. Although alternation and suppression of an image are largely unconscious or involuntary, some pilots can, to some extent, learn to selectively suppress an image or reach conscious control over alternating images (Malkin, 1987). Winterbottom (2006) showed that binocular fusion of a static background scene can partially mitigate the incidence of visual suppression when wearing a monocular semi-transparent (see-through) HMD. However, suppression was not prevented when a dynamic background scene was viewed. These results are consistent with the notion that moving stimuli are more dominant than stationary stimuli during the rivalry process (Fox and Check, 1972; Norman, 2000). To add to the complexity of monocular HMD-induced rivalry problem, several other factors such as exposure time, spatial frequency, size, luminance and contrast level can affect the strength of the stimulus during the rivalry process (Winterbottom, 2006). Binocular rivalry is further discussed in Chapter 12, *Visual Perceptual Conflicts and Illusions*.

Eye dominance is another important factor to consider when viewing imagery through a monocular HMD. Eye or sighting dominance refers to the tendency to prefer one eye over the other for monocular tasks. This consideration is more critical when the design of the monocular HMD does not allow the pilot to select his preference eye—i.e., IHADSS is always displayed to the right eye. The IHADSS monocular design forces the Apache aviator to switch his visual input between the two eyes depending on the required task. Winterbottom (2006) showed that the aviator's ability to intentionally switch dominance between the two visual stimuli can also affect the visibility and detection threshold of targets undergoing rivalry suppression. An ongoing study to determine if the intermittent use of the monocular HMD by British Apache aviators has any long-term effect on binocular visual performance has the potential to clarify the role of eye dominance on aviator's performance while wearing a monocular HMD (Rash and Hiatt, 2005).

Perhaps, one of the greatest disadvantages of monocular HMDs is their reduced FOV. In fact, most Apache pilots partially attribute their physical fatigue and headaches to the narrow FOV provided by the IHADSS (30° [V] by 40° [H]) (Rash and Hiatt, 2005). The extent of available FOV can also be affected by the size of the exit pupil. Light passing through the optical system form an image at the exit pupil, therefore the eye will not capture some of the light rays if the eye is not placed directly at the exit pupil but instead laced behind or in front of it. Issues related to a reduced exit pupil can be overcome by positioning the helmet display unit (HDU) as close as possible to the eye and by maintaining a very stable head-helmet interface. A stable fit of the helmet is paramount to maintain the optimum exit pupil size in the presence of the high-vibration environment of military helicopters (Rash, 1987). These modifications will also maximize the FOV of the monocular HMD system.

Binocular/Biocular viewing

Efficient binocular vision occurs when the retinal image of both eyes are in good focus and of similar size and shape. In particular, both eyes must be capable of aligning themselves in a way that the retinal images of a fixed scene are located at the foveae (i.e., small regions of highest VA) of the two eyes. Proper eye alignment (i.e., motor fusion) results in response to retinal disparity which serves as a cue to activate eyes movement toward one another (i.e., convergence) or away from one another (i.e., divergence). In turn, motor fusion is required to achieve sensory fusion of the images into a single percept. Appropriate levels of motor and sensory fusion will prevent perceptual problems such as diplopia (i.e., double vision), rivalry and suppression as well as visual discomfort and stress (Grosvenor, 1996). Similarly, proper alignment and adjustment of binocular or biocular HMDs, with relation to the Warfighter's eyes, is required to achieve functional vision and prevent visual perceptual problems and eye strain.

An HMD is classified as *binocular* if it presents an identical visual scene to the two eyes from slightly different perspectives via two sensors displaced in space allowing the Warfighter to perceive the image with stereoscopic depth perception or stereopsis. However, a binocular presentation can be achieved using a single sensor if the sensor is manipulated (e.g., temporal delay) to provide two slightly different perspectives of the same visual scene. In contrast, a *biocular* display presents the same image to both eyes from the same perspective so that the resulting view is a two-dimensional display. This is attained using a single sensor as it is the case of the HMD currently in development by Vision System International, San Jose, CA, for the Joint Strike Fighter F-35. Systems that allow binocular perception have substantial advantages over those that provide monocular presentation since binocular visualization is closer to the natural conditions of the human visual system. Unfortunately, from the design point of view, building binocular systems are technically more complex, heavier and of a relative higher cost compared to monocular HMDs. Consequently, their development can call for several design trade-offs.

Generally, binocular and biocular HMDs prevent rivalry and suppression problems usually encountered with monocular HMDs. Moreover, several studies support the notion that binocular vision enhances visual functions such as brightness perception, VA, and contrast sensitivity over the entire spectrum of spatial frequencies as well as the extent of the visual field (Arditi, 1981; Campbell and Robson, 1968; Thorn and Boynton, 1974). These visual improvements are ascribed to binocular summation. As the name implies, binocular summation means that the detection threshold for a stimulus is lower with two eyes than with one; therefore providing an enhanced single binocular percept.

Binocular and binocular HMDs can achieve a larger FOV by presenting a partially overlapped FOV. This is designed to present monocular images to both eyes at the same time with some overlap of the two monocular FOV. Basically, partial overlapped HMDs have a central field of binocular (or biocular in the case of biocular HMDs) overlap region and peripheral regions of monocular viewing (Velger, 1998) and mimics the field of view of the two eyes in unaided vision. Such a partial overlap can be presented by either a convergent or divergent design (Leger, 1994; Rash 2001). A divergent design allows both eyes of the observer to see the central overlap region as well as the right monocular and left monocular regions with the right and left eye, respectively (Figure 10-17). In contrast, a convergent design allows both eyes to see the central overlap region, but the right monocular and left monocular regions are seen only with the left and right eye, respectively (Figure 10-18). For binocular HMDs, optimal conditions for binocular vision are achieved with a convergence design as it resembles the natural mechanism of visual perception and facilitates the processing of binocular disparity cues required to achieve stereopsis (Klymenko, 1994; Leger, 1994; Melzer and Moffitt, 1991). This implies that binocular vision is an essential element to attain stereopsis. Although convergent or divergent partial overlap displays provides larger FOV and stereoscopic advantages, they can potentially create perceptual conflicts such as luning (Figure 10-19). Luning is a subjective darkening in the flanking monocular regions of the FOV near the binocular overlap borders. These regions of luning can interfere with common visual tasks performed by Warfighters such as target detection (Klymenko, 1994).

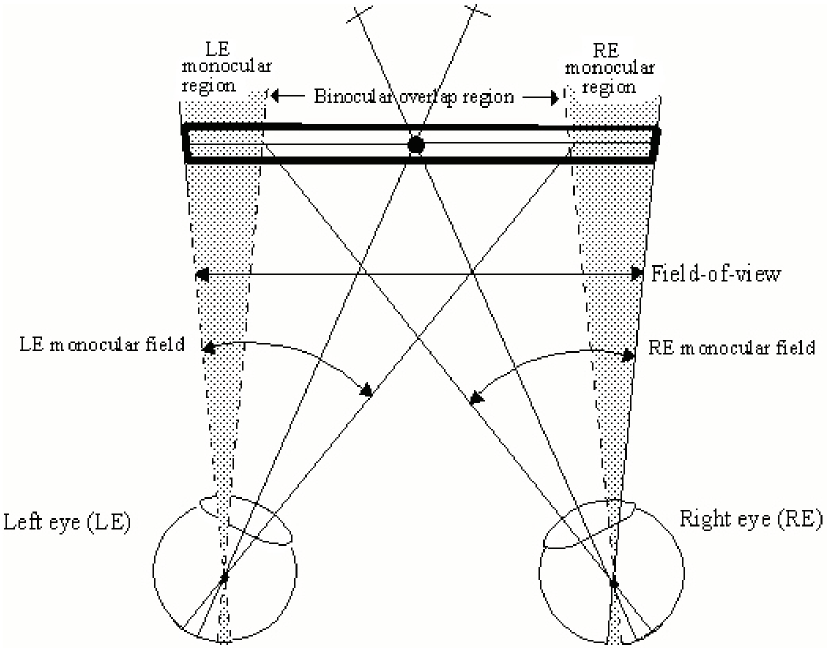


Figure 10-17. Visual interpretation of the divergent display mode of partially-overlapped HMD designs (Rash, 2001).

As discussed in the previous section, *Binocular vs. Monocular Vision*, binocular and biocular HMDs can use partial overlap of the monocular FOVs to achieve a larger FOV. They are designed to present monocular images to both eyes at the same time with some overlap of the two monocular FOV. But in order to provide stereopsis (i.e., binocular HMD) or enhanced monocular cues for depth (i.e., biocular HMDs), part of the available FOV from the two monocular fields must be sacrificed to gain the partial overlap region (Parrish and Williams, 1993). If the partial overlap is created by a binocular HMD system, the resulting central overlap region will provide the binocular disparity cues required to achieve stereopsis. In contrast, if the visual field is provided by a biocular design, the central overlap region of the FOV will only provide monocular cues for perception of depth; thus, cannot provide binocular disparity cues or stereopsis. Moreover, since both eyes of the Warfighter are viewing the same single image with a biocular HMD, the absence of cues for retinal disparity is a strong binocular cue to flatness. This cue to flatness can be in direct conflict with the monocular depth cues that are provided by a single image of the scene (CuQlock-Knoop, 1997). At expense of a reduced FOV, a complete overlap of the images can provide the retina with identical images (i.e., true biocular HMDs) or images with binocular disparity (i.e., binocular HMD) that provides the Warfighter with an extra depth cue.

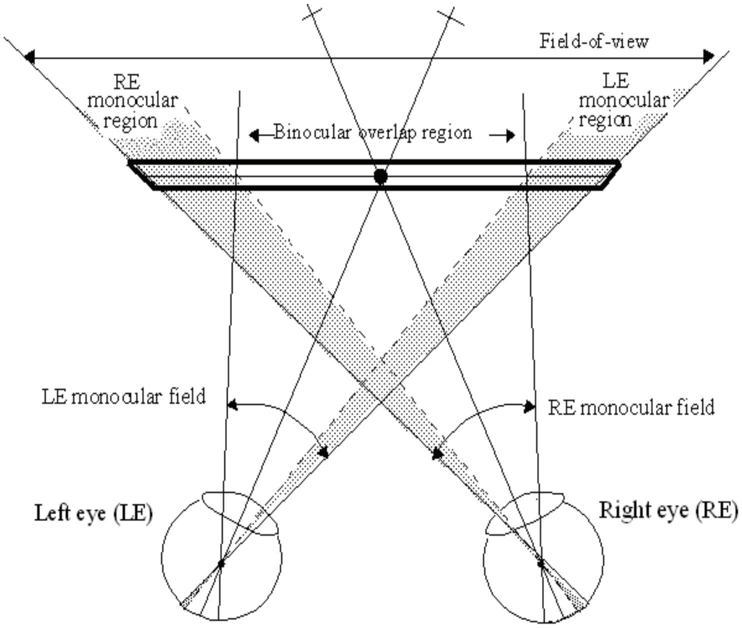


Figure 10-18. Visual interpretation of the convergent display mode of partially-overlapped HMD designs (Rash, 2001).

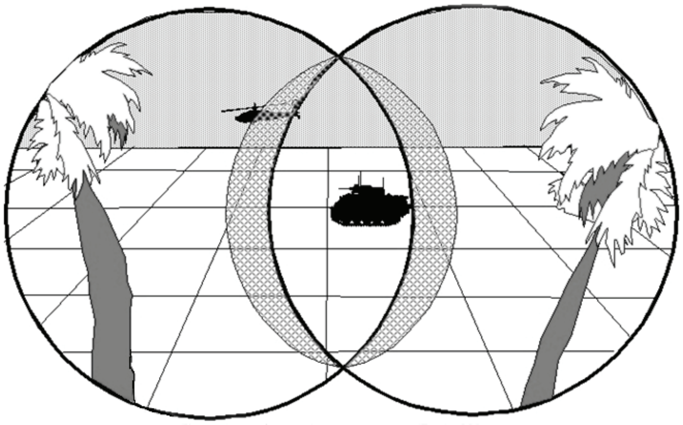


Figure 10-19. Luning in partial overlap displays (Rash, 2001).

The use of binocular or biocular HMDs introduces the possibility to have mismatches between the imagery presented to the two eyes. There are numerous reasons for this, some of which are induced by alignment errors and others by optical image differences. Self (1986) provided a summary of the optical tolerance limits of binocular HMDs in terms of vertical, convergence, and divergence misalignments, as well as rotational, magnification, and luminance differences. Also, proper alignment of the interpupillary distance of the NVG has been determined to be essential to prevent disruption of depth perception (Sheehy and Wilkerson, 1989). A more recent study by Kooi and Toet (2004) using static images demonstrated that in spite of the enhanced perception obtained with stereoscopic displays, a small amount of asymmetry between the two images (i.e., stereo imperfections) has the potential to reduce visual comfort. Stereo imperfections are induced by many factors such as optical errors (i.e., spatial distortions), imperfect filters (i.e., photometric asymmetries including luminance, color, and contrast), and stereoscopic disparities. This study also provides threshold values for the onset of visual discomfort induced by these factors of binocular image imperfections that should be taken into account during the HMD design and selection process.

Binocular cues for depth perception

Binocular cues for depth includes retinal disparity, convergence, and accommodation. Since these are innately determined, these cues come into play during the first few months of life as a consequence of the development and maturation of the visual pathways to the brain. Some neurons in the visual cortex are able to detect retinal disparity and act as depth detectors. Retinal disparity is the predominant cue for depth and results when a scene stimulates disparate (non-corresponding) retinal points in the two eyes. If the amount of retinal disparity is small, the observer will perceive stereopsis; otherwise the observer will experience diplopia. Empirical data by Boff and Lincoln (1988) demonstrated that retinal disparity can provide depth information from a distance up to 264 meters (866 feet). A subsequent study by Roumes et al. (2001) showed that binocular disparity can improve distance estimation using stereoscopic displays with stereo-near configuration – i.e., the point of zero disparity located is at the nearest point visible in the scene – for a range of distances up to 160 meters (525 feet).

Convergence and accommodation provide weak propioceptive (i.e., position sense) cues for depth. Convergence serves as a cue for depth because the convergence of the eyes depends on the distance of the fixating object. Therefore, it provides oculomotor propioceptive information arising from extraocular muscles and changes of the angle of inclination of the eyes. Accommodation also serves as a depth cue because the shape of the lens depends on the distance of the object an observer focuses on. Accommodation of the lens in response to blur provides information concerning position sense arising from the ciliary muscle. A study by Sheehy and Wilkinson (1989) with helicopter pilots that had failed a test of stereoscopic depth perception after a prolonged flight training employing night vision goggles suggested that loss of stereopsis might have been caused by a shift in lateral phorias. In this particular case, it would be expected that as additional fusional effort is required, the minimum resolvable disparity degrades due to increases in accommodation brought about through vergence accommodation.

Monocular cues for depth perception

Monocular cues for perception of depth are empirical cues that must be learned and therefore they are developed more slowly. Monocular cues for depth include relative size, overlay, geometrical perspective, aerial perspective, as well as light and shadow (Grosvenor, 1996) (Figure 10-20). The *relative size* of an image depends upon its distance from the observer. The size of the image is small when the object is far away, and becomes larger as the object approaches the observer. *Overlay* (i.e., interposition) refers on how an object that partially blocks another object is interpreted as being closer. *Geometrical* or *linear perspective* is perhaps the most common monocular cue of depth. The basis for the cue of linear perspective is given by the fact that distant objects necessarily produce a smaller retinal image than nearby objects of the same size. Consequently, the horizontal separation of the two sides of parallel lines (e.g., railroad track, road) converges toward the horizon – larger for the near portion of the parallel lines and smaller for the more distant portions. *Aerial perspective* or height as a monocular cue of depth is based on the perception that the further away an object is from the observer the higher in the visual field its image will be interpreted. The distribution of *light and shadow* on an object is also a dominant monocular cue for depth provided by the assumption that light comes from above. It also takes into account that objects do not usually allow light to pass through, therefore, they will cast a shadow. These monocular cues are of particular importance for Warfighters wearing monocular and biocular HMDs, but they also can offer enhanced details of the viewed scene while wearing a binocular HMD.

In summary, operational and occupational requirements for depth perception or stereopsis will strongly influence the final design of a particular HMD. While binocular HMDs provided the operator with stereopsis and perception of depth when monocular cues are absent, monocular or biocular HMDs can only provide perception of depth when monocular cues are present. Nevertheless, monocular cues enhance the operator's ability to perceived stereopsis while wearing a binocular HMD.

Figure 10-20. This picture of a complex scene demonstrates how monocular cues (relative size, overlay, geometrical perspective, aerial perspective, as well as light and shadow) are used by the human visual system to perceive depth or relative distance between objects in a two dimensional image in the absence of binocular cues.

References

Adelson, E.H. (1999). Lightness perception and lightness illusions. In: *The Cognitive Neurosciences*, Gazzaniga, M., (Ed.), Cambridge, MA: MIT Press.

Adelson, E., and Bergen, J. (1985). Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America A*, 2, 284-299.

Angel, S-D. (2003). IPNVG fixed-focus diopter study. *Proceedings of SPIE, Helmet- and Head-Mounted Displays VIII,* 5079, 154-163.

Angel, S-D., and Baldwin, J.B. (2004). Aircrew visual acuity viewing with different night vision goggle eyepiece diopter settings. *Proceedings of SPIE, Helmet- and Head-Mounted Displays IX*, 5442 1-12.

Anstis, S. (1970). Phi movement as a subtraction process. *Vision Research*, 10, 1411-1430.

Anstis, S. (1978). Apparent movement. In: *Handbook of Sensory Physiology*, Held, R., Leibowitz, H., and Teuber, H.L., (Eds.), *Perception* (Vol. VIII). New York: Springer-Verlag.

Anstis, S., and Rogers, B. (1975). Illusory reversal of visual depth and movement during changes of contrast. *Vision Research*, 15, 957-961.

Arditi, A. (1986). Binocular vision. In: *Handbook of Perception and Human Performance,* Boff, K.R., and Thomas, J.P., (Eds.). New York: Wiley and Sons.

Arditi, A.R., Anderson, P.A., and Movshon, J.A. (1981). Monocular and binocular detection of moving sinusoidal gratings. *Vision Research*, 21, 329-36.

Attneave, F. (1971). Multistability in perception. *Scientific American*, 225, 63-71.

Bailey, I.L., and Lovie, J.E. (1976). New design principles for visual acuity letter charts. *American Journal of Optometry and Physiological Optics*, 53, 740-745.

Bailey, M.D., Mitchell, G.L., Dhaliwal, D.K., Boxer Wachler, B.S., and Zadnik, K. (2003). Patient satisfaction and visual symptoms after laser in situ keratomileusis. *Ophthalmology*, 110, 1371-8.

Barfield, W., and Furness, T.A. (Eds.) (1995). *Virtual Environments and Advanced Interface Designs*. Table 6-13, p. 226. New York: Oxford Press.

Barlow, H., and Hill, R. (1963). Evidence for a physiological explanation of the waterfall phenomenon and figural aftereffects. *Nature (London)*, 200, 1345-1347.

Blake, R., and Sekuler, R. (2005). *Perception* (5th Ed). New York: McGraw-Hill.

Boff, K.R., and Lincoln, J.E. (1988). Engineering data compendium: human perception and performance. Wright-Patterson Air Force Base: Armstrong Aerospace Medical Research Laboratory.

Braddick, O. (1974). A short-range process in apparent motion. *Vision Research*, 14, 519-527.

Braunstein, M.L. (1976). *Depth Perception Through Motion*. New York: Academic Press.

Campbell, F.W., and Robson, J.G. (1968). Application of Fourier analysis to the visibility of gratings. *Journal of Physiology*, 197, 551-66.

Cavanagh, P., and Mather, G. (1989). Motion: the long and short of it. *Spatial Vision*, 4, 103-129.

Cheng, A., Eysel, U., and Vidyasagar, T. (2004). The role of the magnocellular pathway in serial deployment of visual attention. *European Journal of Neuroscience*, 20, 2188-2192.

Chubb, C., and Sperling, G. (1988). Drift-balanced random stimuli: A general basis for studying non-Fourier motion perception. *Journal of the Optical Society of America A*, 5, 1986-2007.

Conticelli, M., and Fujiwara, S. (1964). Visuo-motor reaction time under differential binocular adaptation. In: *Atti Della Foundizone*, Ronchi, G., (Ed.).

Crowley, J.S., Rash, C.E., and Stephens, R.L. (1992). Helmet-Mounted Displays III: Visual illusions and other effects of night vision devices. *Proceedings of SPIE*, 1695, 199-180.

CuQlock-Knopp, V.G., Myles, K., and Merritt, J.O. (1997). Perceptual conflicts between monocular and binocular depth of cues in biocular displays. *Digest*, 97, 955-958.

Cutting, J.E., and Vishton, P.M. (1995). Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In: Epstein, W., and Rogers, S. (Eds.) *Perceptual Space*. New York: Academic Press.

Dahm, M. (2006). *Grundlagen der Mensch-Computer-Interaction*. Munich, Germany: Pearson.

Davidoff, J. (1991). *Cognition through color*. Cambridge, MA: The MIT Press.

Department of Defense. (2001). Interface Standard. *Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible.* MIL-STD-3009.

Defense Supply Agency. (1962). *Military Standardization Handbook 141, Optical Design*. Washington, DC: Defense Supply Agency.

DeMars, S.A. (1975). Human factors considerations for the use of color in display systems. Cape Kennedy, FL: NASA. NASA TR-1329.

Dennis, R.J., Beer, J.M., Baldwin, J.B., Ivan, D.J., Lorusso, F.J., and Thompson, W.T. (2004). Using the Freiburg acuity and contrast test to measure visual performance in USAF personnel after PRK. *Optometry and Vision Science*, 81, 516-24.

Donohue-Perry, M.M., Task, H.L, and Dixon, S.A. (1994). Visual acuity vs. field of view and light level for night vision goggles. *Proceedings of SPIE, Helmet- and Head-Mounted Displays and Symbology Design Requirements*, 2218, 71-81.

Dudfield, H.J. (1991). Colour head-up displays: help or hindrance? *Proceedings of the Human Factors Society 35th Annual Meeting,* 146-150.

Emerson, R., Bergen, J., and Adelson, E. (1992). Directionally selective complex cells and the computation of motion energy in cat visual cortex. *Vision Research*, 32, 203-218.

Epstein, W., Park, J., and Casey, A. (1961). The current status of the size-distance hypothesis. *Psychological Bulletin*, 558(6), 491-514.

Ericksen, C.W., and Ericksen, B.A. (1974). Effects of noise letter upon the identification of a target letter in a nonsearch task. *Perception and Psychophysics*, 16, 143-149.

Exner, S. (1875). Experimentelle Untersuchung der Einfachsten Psychischen Processe. *Archives of Gestalt Physiology*, 11, 403-432.

Fan-Paul, N.I., Li, J., Miller, J.S., and Florakis, G.J. (2002). Night vision disturbances after corneal refractive surgery. *Survey of Ophthalmology*, 47, 533-46.

Farrell, R.J., and Booth, J.M. (1984). *Design Handbook for Imagery Interpretation Equipment.* Seattle: Boeing Aerospace Company.

Fisher, E., Haines, R.F., and Price, T.A. (1980). Cognitive issues in head-up displays. Moffett Field, CA: NASA Ames Research Center. No 1711.

Flinn, S. (2000). Simultaneous contrast: luminance. Retrieved June 1, 2008 from University of British Columbia Web site: http://www.cs.ubc.ca/nest/imager/contributions/flinn/Illusions/ BW/ bw.html

Fox, R., and Check, R. (1972). Independence between binocular rivalry suppression duration and magnitude of suppression. *Journal of Experimental Psychology*, 93, 283-9.

Foyle, D.C., McCann, R.S. Sanford, B.D. and Schwirzke, M.F.J. (1993). *Proceedings of the 37th Annual meeting of the Human Factors and Ergonomics society*, Santa Monica, CA: Human Factors and Ergonomics Society. p. 1340-1344.

Franconeri, S.L., and Simons D.J., (2005). The dynamic events that capture attention: A reply to Abrams and Christ. *Perception and Psychophysics*, 67(6), 962-966.

Gibson, J.J. (1950). *The perception of the visual world*. Boston: Houghton-Mifflin.

Ginsburg, A.P. (1983). Direct performance of HUD systems using contrast sensitivity. In: *Optical and Human Performance Evaluation of HUD System Design*, Martin, W.L., (Ed.), Wright-Patterson AFB, OH: U.S. Air Force Aeromedical Research Laboratory.

Ginsburg, A.P., and Easterly, J. (1983). Contrast sensitivity predicts target detection field performance of pilots. *Proceeding of Human Factors Society*, 27th Annual Meeting. p. 269-273.

Gish, K.W., and Staplin, L. (1995). Human factors aspects of using head up displays in automobiles: A review of the literature. DOT HS 808 320 the Scientex Corp Landsdale PA, for the USDT National Highway Traffic Safety Administration.

Glick, D.D., and Moser, C.E. (1974). Afterimages associated with using the AN/PVS-5, night vision goggle. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL LR 75-1-7-1.

Goldstein, E.B. (2007). *Sensation and Perception* (7th Ed). Belmont, CA: Wadsworth.

Graham, C.H. (1966). Visual space perception. In: Graham, C.H. (Ed.), *Vision and Visual Perception*. New York: John Wiley and Sons, Inc.

Green, D., and Swets, J. (1966). *Signal detection theory and psychophysics*. Huntington, NY: Robert E. Krieger Publishing Company.

Greene, D.A. (1988). Night vision pilotage system field-of-view (FOV)/resolution tradeoff study flight experiment report. Fort Belvior, VA: U.S. Army Night Vision Laboratory. NV 1-26.

Grosvenor, T. (1996). Anomalies of binocular vision. In: *Primary care optometry: Anomalies of refraction and binocular vision*. Boston: Butterworth-Heinemann. p. 105-117.

Happ, A., and Pantle, A. (1987). Visual motion processing and display design. In: L. Mark, L., Warm, J., and Huston, R., (Eds.), E*rgonomics and Human factors: Recent Research*. New York: Springer-Verlag. p. 85-94.

Harding, T.H., Martin, J.S., and Rash, C.E. (2007). The legibility of HMD symbology as a function of background local contrast. *Proceedings of SPIE*, 6557, D1-D8.

Havig, P.R., Grigsby, S.S., Heft, E.L., LaCreta, J.M., and Post, D.L. (2001). Luminance contrast and color recognition in helmet-mounted displays. *Proceedings of SPIE*, 4361, 198-204.

Hering, E. (1878). *Zur Lehre vom Lichtsinne.* Vienna: Carl Gerolds Sohn.

Hermans, T.G. (1937). Visual size constancy as a function of convergence. *Journal of Experimental Psychology*, 21(2), 143-161.

Hooey, B.L., Foyle, D.C., Andre, A.D., and Parke, B. (2000). Integrating datalink and cockpit display technologies into current and future taxi operations. *Proceedings of the AIAA/IEEE 19th Digital Avionics System Conference*, 7.D.2-1 to 7.D.2-8.

Hubel, D., and Wiesel, T. (1962). Receptive fields, binocular interaction and functional architecture in the cat's striate cortex. *Journal of Physiology*, 160, 106-154.

Hubel, D., and Wiesel, T. (1968). Receptive fields and functional architecture of monkey striate cortex. *Journal of Physiology*, 195, 215-243.

Johansson, G. (1973). Visual perception of biological motion and a model for its analysis. *Perception and Psychophysics*, 23, 76-88.

Jonides, J., and Ynatis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception and Psychophysics,* 43(4) 346-354.

Kaiserman, I., Hazarbassanov, R., Varssano, D., and Grinbaum, A. (2004). Contrast sensitivity after wave front-guided LASIK. *Ophthalmology*, 111, 454-457.

Kalich, M.E., Rash, C.E., Thomas H. Harding, T.H., Jennings, S., Craig, G., and Stuart, G.W. (2009). Flight performance using a hyperstereo helmet-mounted display: post-flight debriefing questionnaire. *Proceedings of SPIE, Head-and Helmet-Mounted Displays XIV: Design and Applications,* 7326.

Kalich, M.E., Rash, C.E., McLean, W.E. and Ramiccio, J.G. (2007). A limited flight study for investigating hyperstereo vision. *Proceedings of SPIE, Head-and Helmet-Mounted Displays XII: Design and Applications,* 6557, 65570I1-65570I14.

Klymenko, V., Verona, R.W., Martin, J.S., Beasley, H.H., and McLean, W.E. (1994). The effects of binocular overlap mode on contrast thresholds across the field-of-view as a function of spatial and temporal frequency. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL. USAARL Report No. 94-49.

Kooi, F.L. (1986). Visual strain: a comparison of monitors and helmet-mounted displays. In *Proceedings of SPIE: Imaging Sciences and Display Technologies*, 2949, 162-171.

Kooi, F.L., and Toet, A. (2004). Visual comfort of binocular and 3D displays. *Displays*, 25, 99-108.

Kotulak, J.C., and Rash, C.E. (1992). Visual acuity with second and third generation night vision goggles obtained from a new method of might sky simulation across a wide range of target contrasts. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 92-9.

Larish, I., and Wickens, C.D. (1991). Divided attention with superimposed and separated imagery: Implications for head-up displays (No 91-4/NASA HUD 91-1) Savoy, IL: University of Illinois, Aviation Research Laboratory.

Laycock, J., and Chorley, R.A. (1980). The electro-optical display/visual system interface: Human factors considerations. *Advancements on Visualization Techniques*, AGARD, p. 3/1- 3/15.

Leger, A., Roumes, C., Gardelle, C., Cursolle, J.P., and Kraus, J.M. (1994). Binocular HMD for fixed-wing aircraft: a trade-off approach. *Displays*, 15, 91-97.

Leibowitz, H. (1966). Role of changes in accommodation and convergence in the perception of size. *Journal of the Optical Society of America*, 56(8), 1120-1123.

Lennie, P. (1980). Parallel visual pathways: a review. *Vision Research*, 20, 561-594.

Levin, S.T., Momen, N., Drivdahl, S.B., and Simons, D.J., (2000). Change blindness blindness: The metacognitive error of overestimating change-detection ability. *Visual Cognition*, 7, 399-412.

Levine, R.R., and Rash, C.E. (1989). Visual acuity with AN/PVS-5A night vision goggles and simulated flashblindness protective lenses under varying levels of brightness and contrast. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 89-16.

Livingstone, M., and Hubel, D. (1988). Segregation of form, color, movement, and depth: anatomy, physiology, and perception. *Science*, 240, 740-749.

Lu, Z., and Sperling, G. (2001). Three-systems theory of human visual motion perception: review and update. *Journal of the Optical Society of America A*, 18, 2331-2370.

Luo, X., Kenyon, R., Kamper, D., Sandin, D. and DeFanti, T. (2007). The effects of scene complexity, stereovision, and motion parallax on size constancy in a virtual environment. *Proceedings of Virtual Reality Conference 2007, VR '07, IEEE*, Charlotte, North Carolina, 59-66.

Malkin, F.J. (1987). AH-64A Helmet-mounted display lessons learned. Discussion Paper No. 40. U.S. Army Human Engineering Laboratory. Aberdeen Proving Ground, Maryland.

Marasco, P.L., and Task, H.L. (2003). The impact of target luminance and radiance on night-vision device visual performance testing. *Proceedings of SPIE*, *Helmet- and Head-Mounted Displays VIII*, 5079, 174-183.

Marr, D., and Ullman, S. (1981). Directional selectivity and its use in early visual processing. *Proceedings of the Royal Society London B*, 211, 151-180.

Martinsen, G.L., and Havig, P.R. (2002). Luminance contrast requirements for colored symbols in helmet-mounted displays. Human Effectiveness Directorate, Crewsystem Interface Division. Dayton, OH; U.S. Air Force Research Laboratory.

Mather, G., Verstraten, F., and Anstis, S. (Eds). (1998). *The Motion Aftereffect: A Modern Perspective.* Cambridge, MA: MIT Press.

McCann, R.S., Foyle, D.C., and Johnson. (1993). Attentional limitations with head-up displays. *Proceedings of the7th International symposium of aviation psychology*. 26-29 April 1993. p. 70-75.

McCann, R.S., Lynch J., Foyle, D.C., and Johnson. (1993). Modeling Attentional effects with head-up displays. *Proceedings of the Human Factors and Ergonomics 37th annual meeting,* p. 1345-1349.

McCarthy, J., Pantle, A., and Pinkus, A. (1994). Detection and direction discrimination performance with flicker gratings in peripheral vision. *Vision Research*, 34, 763-773.

McKee, S., and Watamaniuk, S. (1994). The psychophysics of motion perception. In: Smith, A., and Snowden, R. (Eds.), *Visual detection of motion.* London: Academic Press.

Melzer, J.E., and Moffitt, K. (1991). Helmet-mounted displays. An ecological approach to partial binocular overlap. *Proceedings of SPIE*, 1456, 124-131.

McCarthy, J., Pantle, A., and Pinkus, A. (1994). Detection and direction discrimination performance with flicker gratings in peripheral vision. *Vision Research*, 34, 763-773.

McKee, S., and Watamaniuk, S. (1994). The psychophysics of motion perception. In: Smith, A., and Snowden, R. (Eds.), *Visual detection of motion.* London: Academic Press.

Merigan, W., and Maunsell, J. (1993). How parallel are the primate visual pathways. *Annual Review of Neuroscience*, 16, 369-402.

Miller, R., Provines, W., Block, M., Miller, J., and Tredici, T. (1984). Comparative visual performance with ANVIS and AN/PVS-5A night vision goggles under starlight conditions. Brookes AFB, TX: USAF School of Aerospace Medicine. Technical Report No. USAFSAM-TR-84-28.

Moffitt, K., Rogers, S.P., and Cicinelli, J. (1988). Chromatic aftereffects associated with a night vision goggle simulation. *Aviation, Space, and Environmental Medicine*, 59(2), 125-128.

Mon-Williams, M., and Wann, J.P. (1998). Binocular virtual reality displays: When problems do and don't occur. *Human Factors*, 40(1), 42-49.

Movshon, A., and Newsome, W. (1992). Neural foundations of visual motion perception. *Current directions in psychological science*, 1, 35-39.

Movshon, A., and Newsome, W. (1996). Visual response properties of striate cortical neurons projecting to Area MT in macaque monkeys. *Journal of Neuroscience*, 16, 7733-7741.

Mrochen, M., Kaemmerer, M., Mierdel, P., and Seiler, T. (2001). Increased higher-order optical aberrations after laser refractive surgery: a problem of subclinical decentration. *Journal of Cataract and Refractive Surgery*, 27, 362-369.

Murakami, I., and Shimojo, S. (1996). Assimilation-type and contrast-type bias of motion induced by the surround in a random-dot display: evidence for center-surround antagonism. *Vision Research*, 36, 3629-3639.

National Academy of Sciences. (1980). Recommended standard procedures for the clinical measurement and specification of visual acuity. *Report of Working Group 39, Committee on Vision*, *Advances in Ophthalmology,* 41*,* 103-148.

National Aeronautics and Space Administration. (2008). Color discrimination and identification. Retrieved 5 October 2008 from NASA Ames Research Center website: http://colorusage.arc.nasa.gov/discrim.php

Nawrot, M., and Sekuler, R. (1990). Assimilation and contrast in motion perception: explorations in cooperativity. *Vision Research*, 10, 1439-1451.

Newsome, W., Britten, K., and Movshon, J. (1989). Neuronal correlates of a perceptual decision. *Nature*, 341, 52-54.

Newsome, W., and Pare, E. (1988). A selective impairment of motion perception following lesions of the middle temporal visual area (MT). *Journal of Neuroscience*, 8, 2201-2210.

Norman, H.F., Norman, J.F., and Bilotta, J. (2000). The temporal course of suppression during binocular rivalry. *Perception*, 29, 831-41.

Ogle, K.N. (1950). *Research in binocular vision*. Philadelphia, PA: Saunders.

Ogle, K.N., and Schwartz, J.T. (1959). Depth of focus of the human eye. *Journal of the Optical Society of America*, 49, 273-80.

Oram, M., and Perrett, D. (1994). Responses of anterior superior temporal polysensory (STPa) neurons to “biological motion” stimuli. *Journal of Cognitive Neuroscience*, 6, 99-116.

Owsley, C., Sekuler, R., and Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research*, 23, 689-99.

Owsley, C., and Sloane, M.E. (1987). Contrast sensitivity, acuity, and the perception of real-world targets. *British Journal of Ophthalmology*, 71, 791-6.

Palmer, S. (1999). *Vision Science*. Cambridge, MA: MIT Press.

Pantle, A. (1973). Stroboscopic movement based upon global information in successively presented visual patterns. *Journal of the Optical Society of America*, 63, 1280A.

Pantle, A., and Picciano, L. (1976). A multi-stable movement display: Evidence for two separate motion systems in humans. *Science*, 193, 500-502.

Pantle, A., and Sekuler, R. (1968). Velocity-sensitive elements in human vision: Initial psychophysical evidence. *Vision Research*, 8, 445-450.

Pantle, A. (1992). Immobility of some second-order stimuli in human peripheral vision. *Journal of the Optical Society of America A*, 9, 863-867.

Pantle, A., and Turano, K. (1992). Visual resolution of motion ambiguity with periodic luminance- and contrast-domain stimuli. *Vision Research*, 32, 2093-2106.

Parkhurst, D., Law, K., and Niebur, E. (2002). Modeling the role of salience in the allocation of overt visual attention. *Vision Research*, 42, 107-123.

Parrish, R.V., and Williams, S.P. (1993). Trade-offs arising from mixture color cueing and monocular, binocular and stereoscopic cueing information for simulated rotorcraft flight. CECOM Technical report 92-B-014. NASA Technical Paper 3268.

Patterson, R., Winterbottom, M.D., and Pierse, B.J. (2006). Perceptual issues in the use of head-mounted visual displays. *Human Factors*, 48, 555-573.

Peli, E. (1995). Real vision and virtual reality. *Optics and Photonics News*, July. p. 28-34.

Petersik, J. (1989). The two-process distinction in apparent motion. *Psychological Bulletin*, 106, 107-127.

Petersik, J., and Pantle, A. (1979). Factors controlling the competing sensations produced by a bistable stroboscopic motion display. *Vision Research*, 19, 143-154.

Pinkus, A.R., Task, H.L., Dixon, S.A., Barbato, M.H., and Hausmann, M.A. (2003). Twenty-Plus Years of Night Vision Technology: Publications and Patents From the Crew System Interface Division of the Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio. Wright-Patterson AFB, OH: Air Force Research Laboratory. Report No. AFRL-HE-WP-TR-2003-0048.

Pinkus, A.R., and Task, H.L. (2000). Night vision goggles (NVG) objective lens focusing methodology and effects of aircraft canopies on NVG focus. *Proceedings of the 2000 SAFE Association Symposium*, Reno, NV, October 9-11, 2000.

Pinkus, A.R., and Pantle, A. (1997). Probing visual motion signals with a priming paradigm. *Vision Research*, 37, 541-552.

Pinkus, A.R., Poteet, M., and Pantle, A. (2008). Dynamic stimulus enhancement with Gabor-based filtered images. *Proceedings of SPIE*, 6968, 69681R.

Pinkus, A.R., Task, H.L., Dixon, S., and Goodyear, C. (2000). Reproducibility limits of night vision goggle visual acuity measurements. *SAFE Journal,* 30(1), 31-139.

Pinkus, A.R., Task, H. L., Dixon, S., and Goodyear, C. (1999). Reproducibility of night vision goggle visual acuity measurements using Landolt C's. *Proceedings of the 1999 SAFE Association Symposium*, Atlanta, GA, December 6-8, 1999.

Pinkus, A.R., and Task, H.L. (1998). Measuring observers' visual acuity through night vision goggles. Wight-Patterson AFB, OH: U.S. Air Force Research Laboratory. Technical Report No. ASC98-1884.

Pinkus, A.R., and Task, H. L. (1997). The effects of aircraft transparencies on night vision goggle-mediated visual acuity. *Proceedings of the 1997 SAFE Association Symposium*, Phoenix, AZ, September 8, 1997.

Post, D.L., Monnier, P., and Calhoun, C.S. (1997). Predicting color breakup on field-sequential displays. *Head-Mounted Displays II, Proceedings of SPIE*, 3058, 57-65.

Post, D.L., Sarma, K.R., Trimmier, J.R., Heinze, W.C., Rogers, J.C., Ellis, R.K., Larson, B.D., and Franklin, H. (1994). A new color display for head-mounted use. *Journal of the Society of Information Display*, 2(4), 155-163.

Prinzel III, L.J., and Risser, M. (2004). Head-up displays and attention capture. NASA Langley Research Center NASA/TM-2004-213000 Hampton VA.

Priot, A., Houlier, S., Guillaume, G., Leger, A., and Roumes, C. (2006). Hyperstereopsis in night vision devices:Basic mechanisms and impact for training requirements. *Helmet- and Head-Mounted Displays X: Technologies and Applications. Proceedings of SPIE*, 6224, 6224ON-1 to 6224ON-11.

Rabin, J. (1993). Spatial contrast sensitivity through aviator's night vision imaging system. *Aviation, Space, and Environmental Medicine*, 64, 706-10.

Rabin, J. (1996). Comparison between green and orange visual displays. *Journal of the Society of Information Display*, 4(2), 107-110.

Rash, C.E. (Ed.) (2001). *Helmet-Mounted Displays: Design Issues for Rotary-Wing Aircraft*. Bellingham, WA: SPIE.

Rash, C.E., Verona, R.W., and Crowley, J.S. (1990). Human factors and safety considerations of night vision systems flight using thermal imaging systems. *Proceedings of SPIE, Helmet-Mounted Displays II*, 1290, 142-164.

Rash, C.E., and Hiatt, K.L. (2005). Apache flight experience in Operation Iraqi Freedom (OIF) shows reduced incidents of visual illusions and problems with the monocular helmet-mounted display. *American Helicopter Society 61st Annual Forum*, 51-66.

Rash, C.E., Kalich, M.E., and van de Pol, C. (2002). Solutions to helmet-mounted display visual correction compatibilities issues. *Proceedings of SPIE*, 4711, 270-289.

Rash, C.E., Martin, J.S., Gower, D.W., Licina, J.R., and Barson, J.V. (1987). Evaluation of the U.S. Army fitting program for the Integrated Helmet Unit of the Integrated Helmet and Display Sighting System. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 87-8.

Rash, C.E., Suggs, C.L., Mora, J.C., van de Pol, C., Reynolds, V.S., and Crowley, J.S. (2001). Visual issues survey of AH-64 Apache aviators (Year 2000). Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 2002-02.

Regan, D., and Beverley, I. (1978). Illusory motion in depth: aftereffect of adaptation to changing size. *Vision Research*, 18, 209-212.

Reichardt, W. (1961). Autocorrelation, a principle for the evaluation of sensory information by the central nervous system. In: Rosenblith, W.A., (Ed.), *Sensory Communication*. New York: Wiley.

Reinhart, W.F., and Post, D.L. (1996). Human factors of two-primary color AMLCDs. *Proceedings of SPIE, Head-mounted Displays*, 2735, 105-114.

Riegler, J.T., Whiteley, J.D., Task, H.L., and Schueren, J. (1991). The effect of signal-to-noise ratio on visual acuity through night vision goggles. Wright-Patterson AFB, OH: Armstrong Laboratory. Report No. AL-TR-1991-0011.

Robson, J. (1966). Spatial and temporal contrast sensitivity functions of the visual system. *Journal of the Optical Society of America*, 56, 1141-1142.

Rodman, H., and Albright, T. (1987). Coding of visual stimulus velocity in area MT of the macaque. *Vision Research*, 27, 2035-2048.

Roscoe, S.N. (1984). Judgements of size and distance with imaging displays. *Human Factors*, 26(6), 617-629.

Roumes, C., Meehan, J. W., Plantier, J., and Menu, J. (2001). Distance estimation in a 3-D imaging display. *The International Journal of Aviation Psychology*, 11, 381-396.

Sanford, B.D., Foyle, D. C., McCann, R.S., and Jordan K. (1993). Head-up displays: effects of information location on the processing of superimposed symbology. In: *Proceedings of the 7th International Symposium on Aviation Psychology*, Jensen, R.S. (Ed.), p. 81- 87.

Schulte-Pelkum, J., Riecke, B. and von der Heyde, M. (2003). Influence of display parameters on perceiving visually simulated ego-rotations—a systematic investigation. Poster presented at TWK 2003, Tubingen, Germany.

Sekuler, R., and Ganz, L. (1963). Aftereffect of seen motion with a stabilized retinal image. *Science*, 139, 419-420.

Sekuler, R., and Pantle, A. (1967). A model for the aftereffects of seen movement. *Vision Research*, 7, 427-439.

Sekuler, R., Pantle, A., and Levinson, E. (1978). Physiological basis of motion perception. In: *Handbook of Sensory Physiology*, Held, R., Leibowitz, H., and Teuber, H-L., (Eds.), *Perception* (Vol. VIII). New York: Springer-Verlag.

Sheehy, J.B., and Wilkinson, M. (1989). Depth perception after prolonged usage of night vision goggles. *Aviation, Space, and Environmental Medicine*, 60, 573-9.

Shelden, S.G., Foyle, D. C., and McCann, R. S. (1997). Effects of scene-linked symbology on flight performance. *Proceedings of the 41st Annual meeting of the Human Factors and Ergonomics Society*, Santa Monica, CA: Human Factors and Ergonomics Society. p. 294-298.

Self, H.C. (1986). Optical tolerances for alignment and image difference for binocular helmet-mounted displays. Dayton, OH: Armstrong Aerospace Medical Research Laboratories. AMRL-TR-86-109.

Simoncelli, E., and Heeger, D. (1998). A model of neuronal responses in visual Area MT. *Vision Research*, 38, 743-761.

Simpson, W.A. (1989). The Step method: A new adaptive psychophysical procedure. *Perception and Psychophysics,* 45(6), *572-576.*

Smith, A. (1994). The detection of second-order motion. In: Smith, A., and Snowden, R., (Eds.), *Visual Detection of Motion.* London: Academic Press.

Smith, A., Greenlee, M., Singh, K., Kraemer, F., and Hennig, J. (1998). The processing of first- and second-order motion in human visual cortex assessed by functional magnetic resonance imaging (fMRI). *Journal of Neuroscience*, 18, 3816-3830.

Snowden, R., and Braddick, O. (1989). Extension of displacement limits in multiple-exposure sequences of apparent motion. *Vision Research*, 29, 1777-1787.

Spenkelink, G.P.J., and Besuijen, J. (1996). Chromaticity contrast, luminance contrast, and legibility of text. *Journal of Society of Information Display*, 4(3), 135-144.

Steinman, B., Steinman, S., and Lehmkuhle, S. (1997). Transient visual attention is dominated by the magnocellular stream. *Vision Research,* 37, 17-23.

Stevens, S.S. (1951). Mathematics, measurement, and psychophysics. In: Stevens, S.S. (Ed.), *Handbook of Experimental Psychology*. New York: John Wiley and Sons, Inc. p.1-49.

Strout, J., Pantle, A., and Mills, S. (1994). An energy model of interframe interval effects in single-step apparent motion. *Vision Research*, 34, 3223-3240.

Swamy, S., Joseph, C., Aravind, A.S., and Vevail, R.J. (2002). Contrast sensitivity in IAF aircrew. *Indian Journal of Aerospace Medicine*, 46, 7-22.

Tanaka, H., Fukada, Y., and Saito, H. (1989). Underlying mechanisms of the response specificity of expansion/contraction and rotation cells in the dorsal part of the medial superior temporal area of the macaque monkey. *Journal of Neurophysiology*, 62, 642-656.

Tanaka, H., and Saito, H. (1989). Analysis of motion of the visual field by direction, expansion/contraction, and rotation cells clustered in the dorsal part of the medial superior temporal area of the macaque monkey. *Journal of Neurophysiology*, 62, 626-641.

Task, H.L., and Marasco, P.L. (2004). The impact of changing night-vision goggle spectral response on night-vision imaging system lighting compatibility. Proceedings of SPIE, *Helmet- and Head-Mounted Displays IX*, 5442, 64-72.

Task, H.L. (2001). Night vision goggle visual acuity assessment: results of an interagency test. *Proceedings of SPIE, Helmet- and Head-Mounted Displays VI*, 4361, 130-137.

Task, H.L. (2000). Integrated panoramic night vision goggles fixed-focus eyepieces: selecting a diopter setting. *Proceedings of the 2000 SAFE Association Symposium*, Reno, NV, October 9-11, 2000.

Task, H.L., Riegler, J., and Goodyear, C. (1999). Effects of laser eye protection and aircraft windscreens on visual acuity through night vision goggles. *Proceedings of the 1999 SAFE Association Symposium*, Atlanta, GA, December 6-8.

Task, H.L., and Pinkus, A.R. (1987). Contrast sensitivity and target recognition performance: A lack of correlation. *1987 Society for Information Display International Symposium Digest of Technical Papers, 18,* 127-129.

Task, H.L., and Genco, L.V. (1986). *Contrast Sensitivity Function Measurement Chart and Method.* U.S. Patent No. 4,607,923.

Thorn, F., and Boynton, R.M. (1974). Human binocular summation at absolute threshold. *Vision Research,* 14, 445-458.

Tredici, T.J., and Ivan, D.J. (2008). Ophthalmology in aerospace medicine. In: *Fundamentals of Aerospace medicine*, Davis, Johnson, Tepanek and Fogarty, (Eds.). New York: Lippincott Williams and Wilkins.

Vaina, L., Cowey, A., and Kennedy, D. (1999). Perception of first- and second-order motion: separable physiological mechanisms. *Human Brain Mapping*, 7, 67-77.

van Nes, F., Koenderink, J., Nas, H. and Bouman, M. (1967). Spatiotemporal modulations transfer in the human eye. *Journal of the Optical Society of America*, 57, 1082-1088.

van Santen, J., and Sperling, G. (1984). Temporal covariance model of human motion perception. *Journal of the Optical Society of America A*, 1, 451-473.

van Santen, J., and Sperling, G. (1985). Elaborated Reichardt detectors. *Journal of the Optical Society of America A*, 2, 300-321.

van de Pol, C., Greig, J.L., Estrada, A., Bissette, G.M., and Bower, K.S. (2007). Visual and flight performance recovery after PRK or LASIK in helicopter pilots. *Aviation, Space, and Environmental Medicine,* 78, 547-53.

Velger, M. (1998). *Helmet-Mounted Displays and Sights*. Boston, MA: Artech House.

Ververs, P.M., and Wickens, C.D., (1998). Conformal flight path symbology for head-up displays: Defining the distribution of visual attention in three-dimensional space. (University of Illinois Institute of Aviation Tech Report No. ARL-98-5/NASA-98-1) Savoy, Ill: Aviation Research Laboratory.

Wagner, M. (2006a). Effects of context on judgements of distance, area, volume, and angle. In: Wagner, M. (Ed.), *The Geometries of Visual Space*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Wagner, M. (2006b). Factors affecting size constancy. In: Wagner, M. (Ed.), *The Geometries of Visual Space*. Mahwah, New Jersey: Lawrence Erlbaum Associates, Inc.

Watson, A., and Ahumada, A. (1985). Model of human visual-motion sensing. *Journal of the Optical Society of America A*, 322-342.

Watson, A., Ahumada, A. and Farrell, J. (1986). Window of visibility: a psychophysical theory of the fidelity in time-sampled visual motion displays. *Journal of the Optical Society of America A*, 3, 300-307.

Wenzel, B., Castillo, A., and Baker, G. (2002). Assessment of the virtual environment safe-for-maintenance trainer (VEST). Air Force Research Laboratory, Human Effectiveness Directorate, Warfighter Training Research Division, Mesa, AZ.

Westheimer, G. (2004). Center-surround antagonism in spatial vision: retinal or cortical locus. *Vision Research*, 44(21) 2457-2465.

Wickens, C.D., and Long J. (1995). Object versus space-based models of visual attention: Implication for the design of head-up displays. *Journal of Experimental Psychology: Applied,* 1(3), 179-193.

Wiley, R.W. (1989). Visual acuity and stereopsis with night vision goggles. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 89-9.

Wiley, R.W., and Holly, F.F. (1976). Vision with the AN/PVS-5 night vision goggle. Neuilly-sur-Seine, France: *AGARD*, 191, C7.1-C.12.

Winterbottom, M.D., Patterson, R., Pierce, B.J., and Taylor, A. (2006). Helmet- and Head-Mounted Displays XI: Technologies and Applications. Visual suppression of monocular presented symbology against a fused background in a simulation and training environment. *Proceedings of SPIE*, 6224, 1-10.

Witt, H. (2007). Human-computer interfaces for wearable computers: A systematic approach to development and evaluation. Doctorial Dissertation, University of Bremen.

Wood, R.B., and Howells, P.J. (2007). Head-up displays. In: *Avionics*, Spitzer, C.R., (Ed.). New York: CRC Press.

Woodworth, R.S., and Schologberg, H. (1954). Visual depth perception. In: Woodworth, R.S., and Schlosberg, H. (Eds.), *Experimental Psychology: Revised Edition*. New York: Holt, Pinehart and Winston.

Yamane, N., Miyata, K., Samejima, T., Hiraoka, T., Kiuchi, T., Okamoto, F., Hirohara, Y., Mihashi, T., and Oshika, T. (2004). Ocular higher-order aberrations and contrast sensitivity after conventional laser in situ keratomileusis. *Investigative Ophthalmology and Visual Science*, 45, 3986-90.

Yeh, M., Merlo, J.M., Wickens, C.D., and Brandenburg, D.L. (2003). Head up versus head down: The costs of imprecision, unreliability, and visual clutter on cue effectiveness for display signaling. *Human Factors,* 45(3), 390-407.

Yeh, M., Wickens, C.D., and Seagull, F.J. (1998). Effects of frame of references and viewing condition on attentional issues with helmet-mounted displays (University of Illinois Institute of Aviation Tech Report No. ARL-98-1/ARMY-FED-LAB-98-1) Savoy, Ill: Aviation Research Laboratory.

Zalevski, A., Meehan, J.W., and Hughes, P.K. (2001). *Size Estimation with Night Vision Goggles.* Fishermans Bend, Victoria, Australia: Department of Defence, Defence Science and Technology Organisation (DSTO), Aeronautical and Maritime Research Laboratory. AR-011-775

Zhang, X., and Farrell, J.E. (2003). Sequential color breakup measured with induced saccades. *Proceedings of SPIE, Human Vision and Electronic Imaging VIII*, 5007, 210-217.